Studying dark matter with gravitational lenses

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UCLA

image: ESA/Hubble, NASA, Suyu et al.

What does cosmology tell us about dark matter?

Dark matter drives structure formation in the universe.

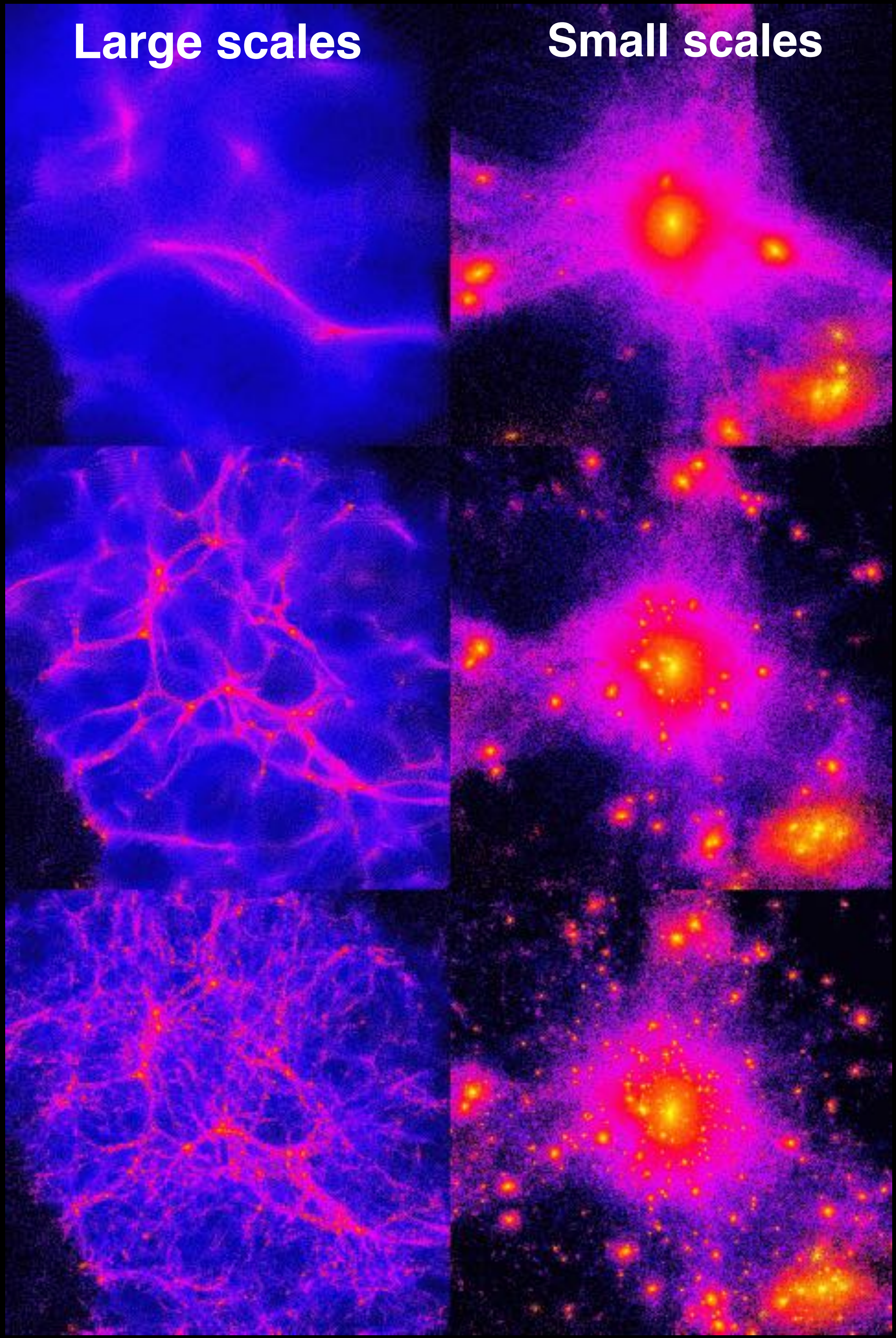


image credit: ITC @ University of Zurich

DM physics encoded in the properties (abundance, density profile) of DM halos

Example: free-streaming length/mass ~ velocity distribution of DM at early times

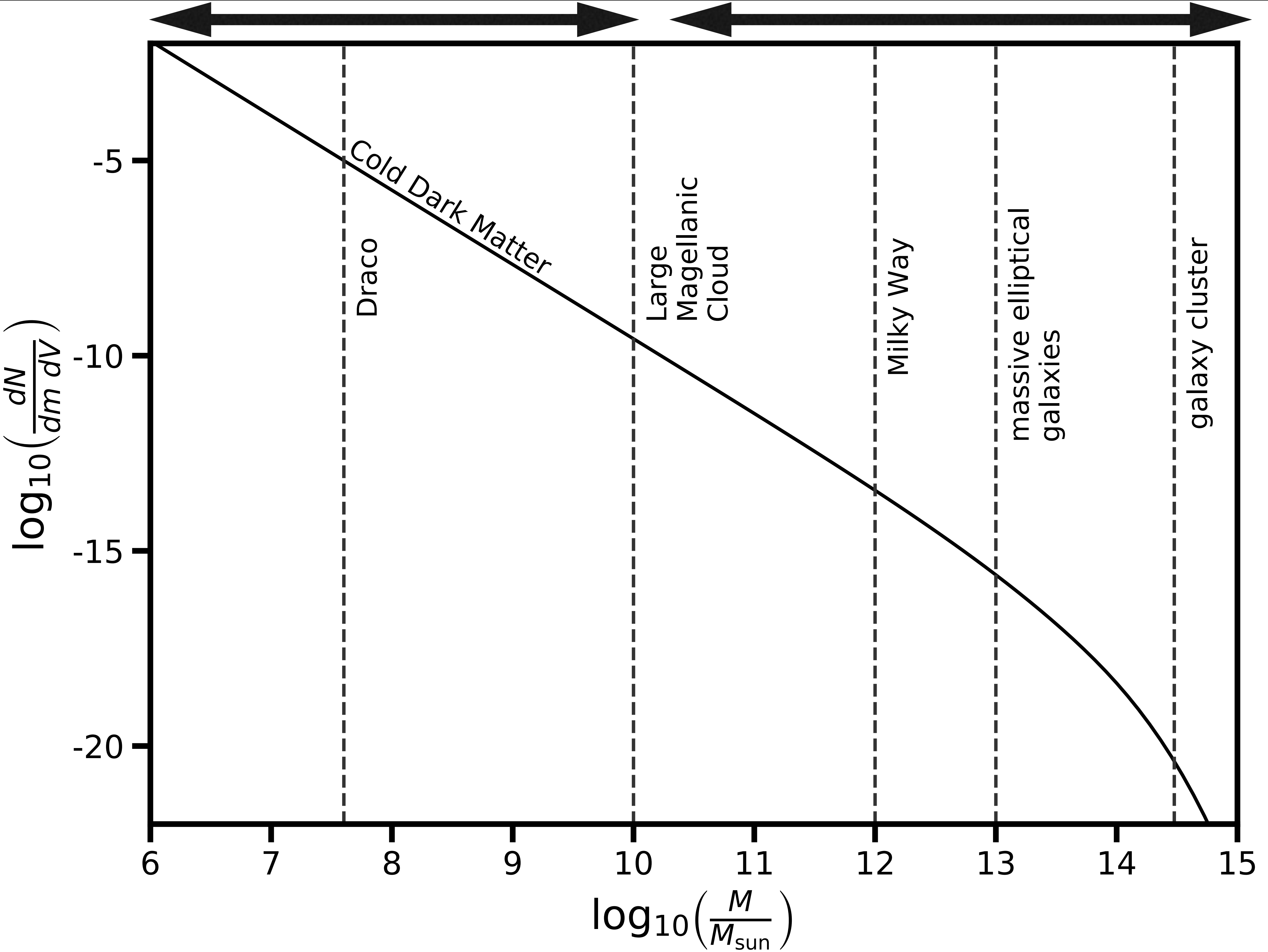
Top: "hot" dark matter
- free streaming mass ~ 10^13 solar masses; no structure below this scale
- ruled out

Middle: "warm" dark matter
- structure suppressed below ~10^8 solar masses (dwarf galaxies)
- example: some sterile neutrino models

Bottom: "cold" dark matter
- free streaming mass ~ 1 Earth mass
- structure on all scales
- example: WIMPS

General prediction of particle DM: galaxies should be surrounded by thousands of small dark matter halos

- halos completely/mostly dark
- can use luminous matter to trace DM



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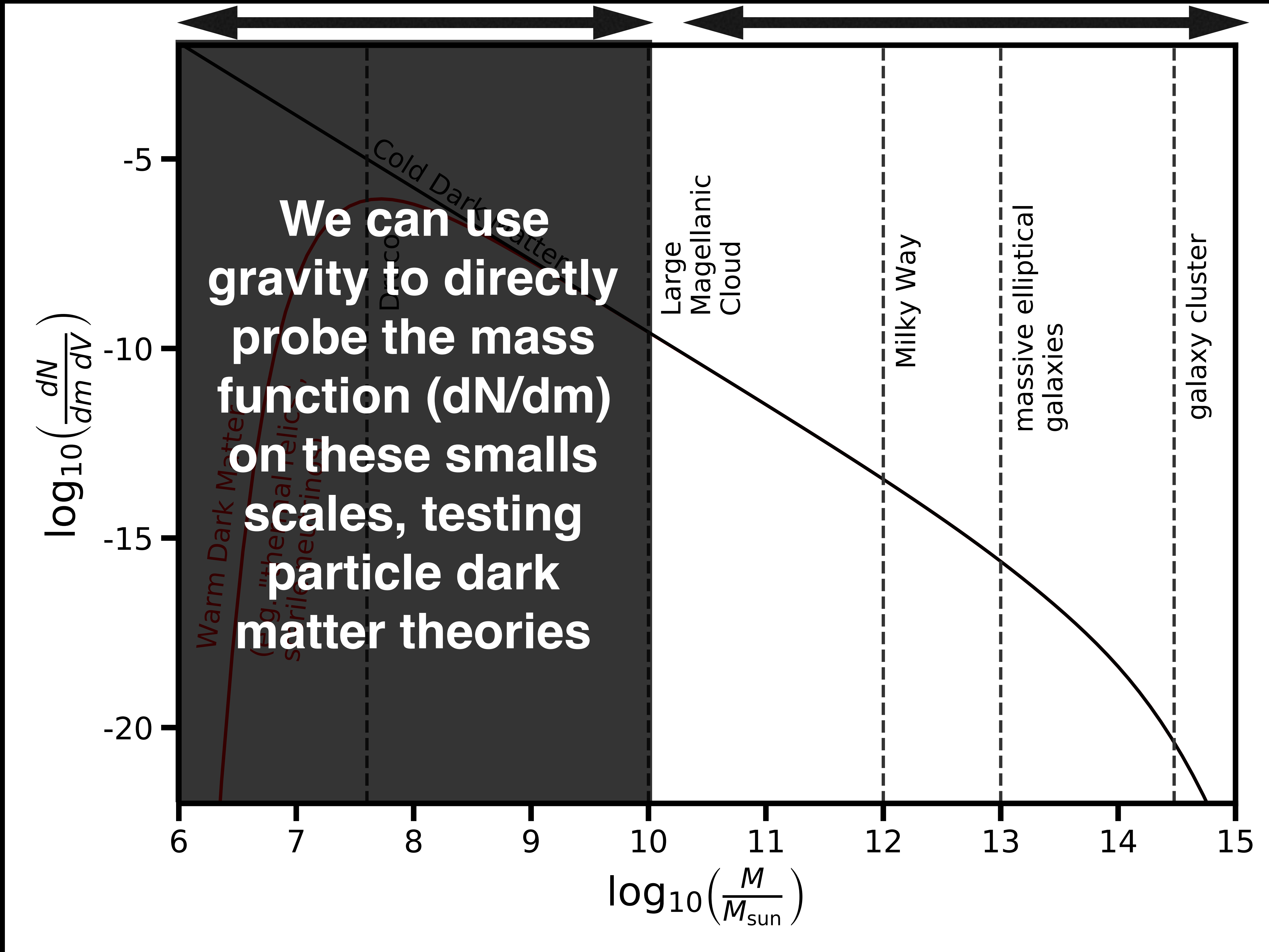
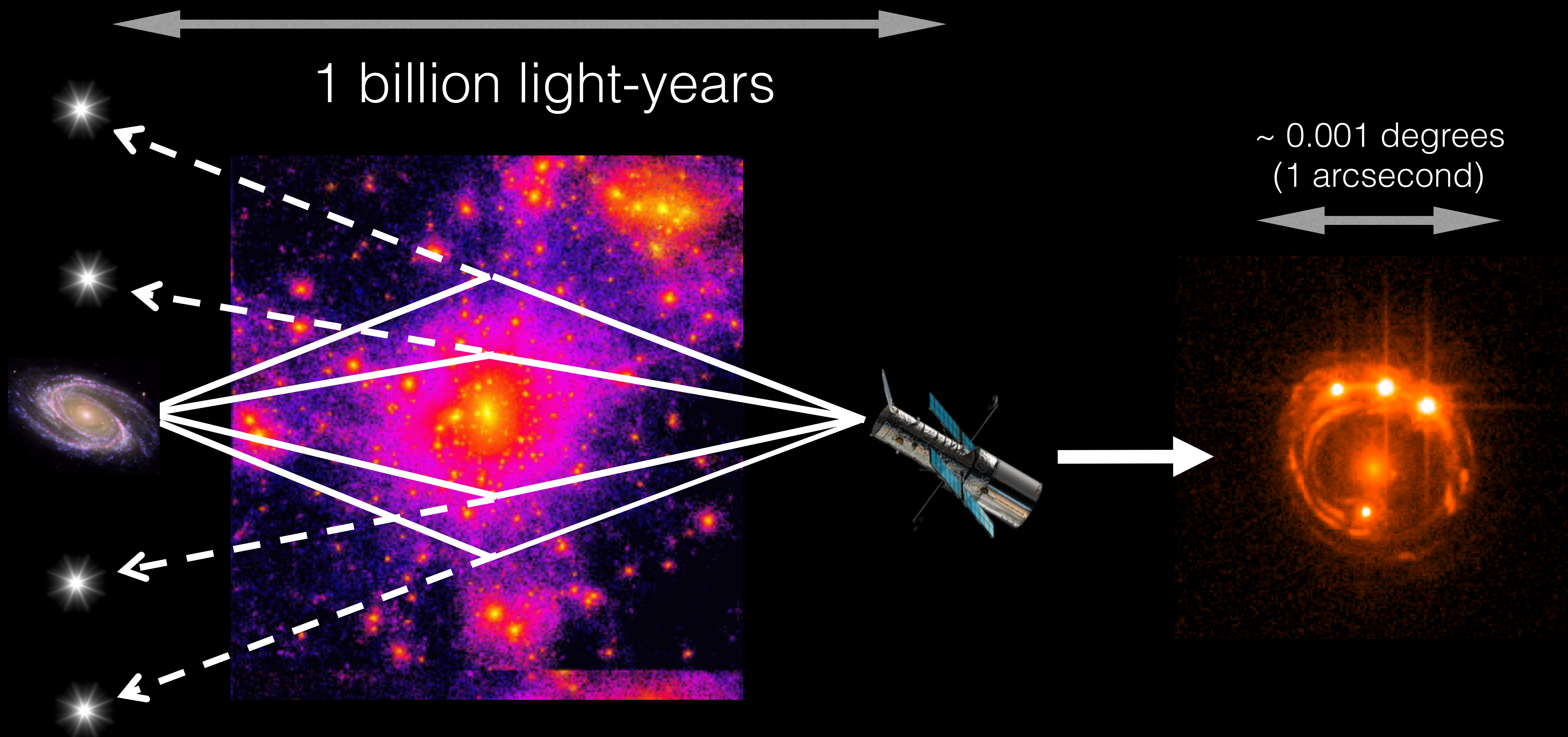


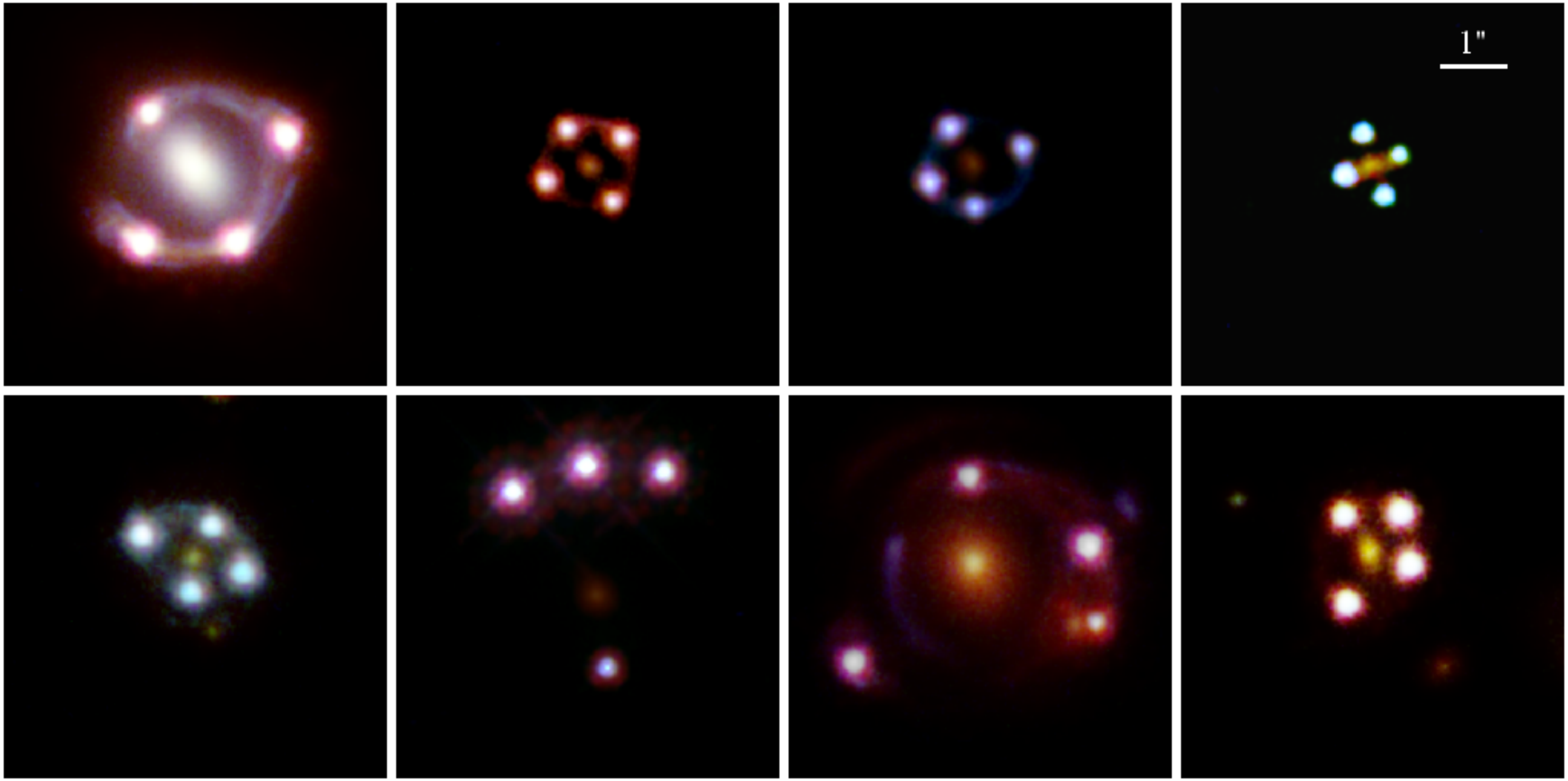
We can use gravity to directly probe the mass function (dN/dm) on these smalls scales, testing particle dark matter theories

~~Gravitational~~ Lensing

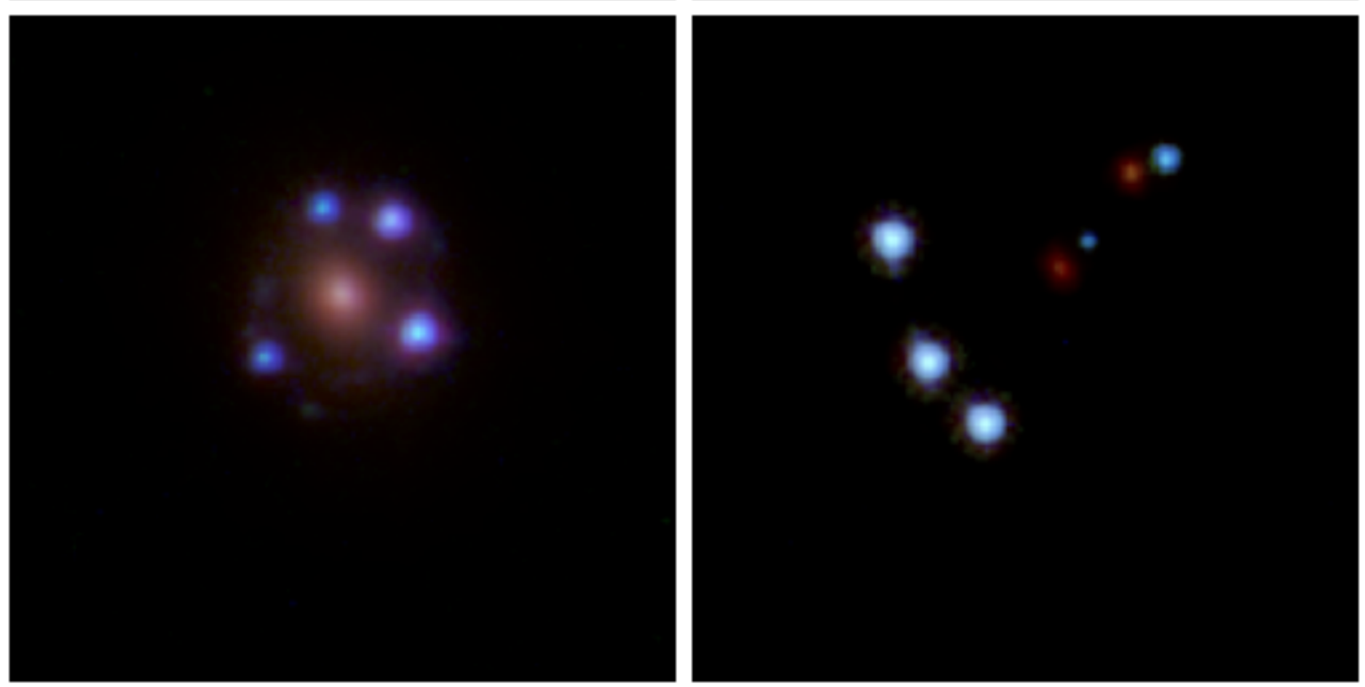
movie by Yashar Hezaveh

Gravitational Lensing





Observables:
1) luminous arcs
and / or
2) time delays
3) positions
4) magnification ratios



Shajib et al 2018 (in prep)

Multiple images arrive at different times:

theta : image plane coordinates
beta : source plane coordinates
psi : lens gravitational potential

$$t\left(\vec{\theta},\vec{\beta}\right)=\frac{D_t}{c}\left(\underbrace{\frac{1}{2}(\vec{\theta}-\vec{\beta})^2}_{\text{geometry}}-\underbrace{\Psi(\vec{\theta})}_{\text{G.R.}}\right)$$

Observable:
time delay

Depends on:
gravitational potential

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Observable:
time delay

Depends on:
gravitational potential

Fermat's Principle
-> light rays arrive at extrema of time delay surface

$$\vec{\beta}=\vec{\theta}-\frac{\partial\Psi(\ \vec{\theta}\ )}{\partial\vec{\theta}}=\vec{\theta}-\alpha(\ \vec{\theta}\ )$$

Observable:
image positions

$$\vec{\theta}_l;\quad l=1,2,3,4$$

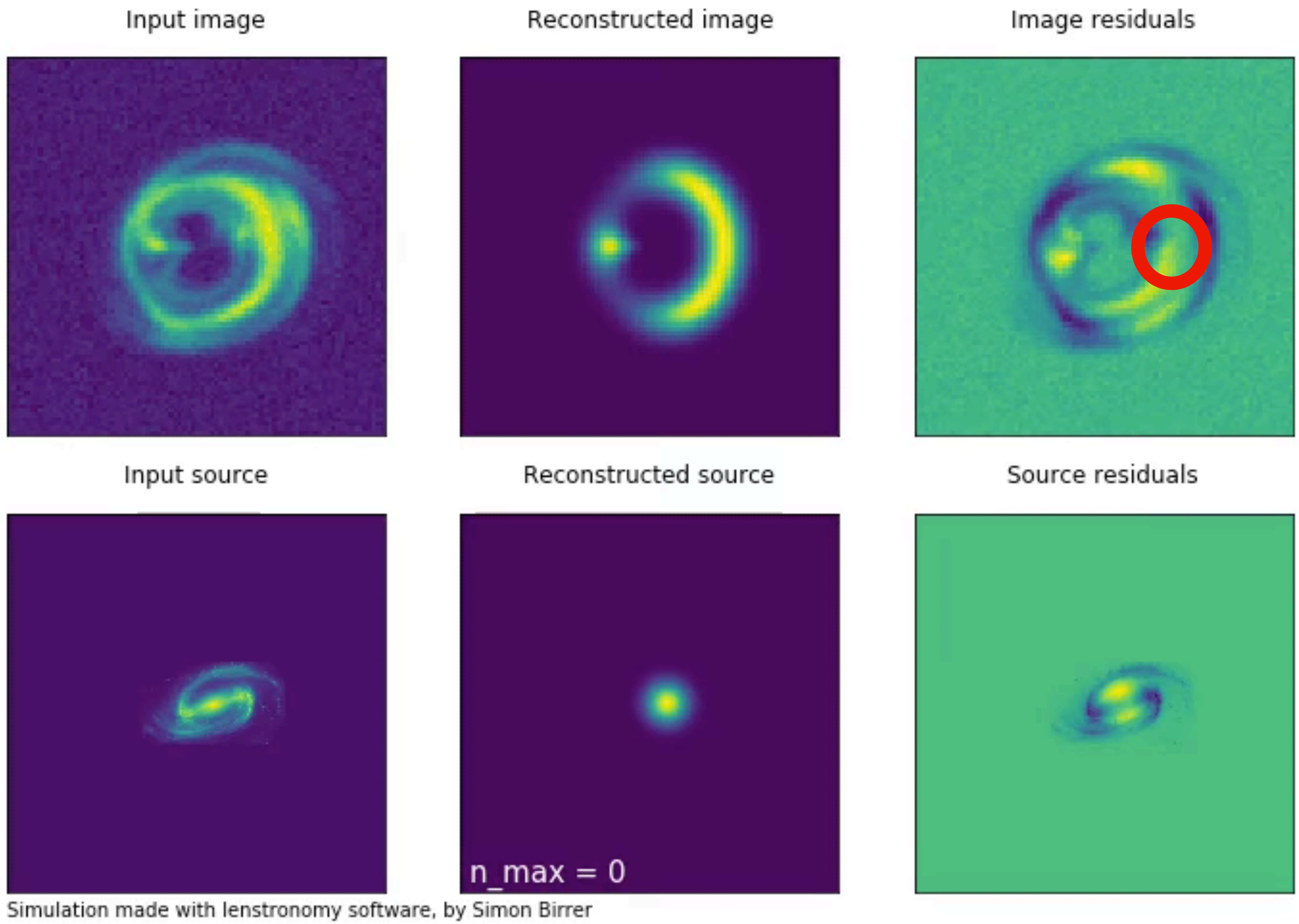
Depends on:
1st derivative of potential

-global deflector mass profile

Technique that wields deflections (1st derivatives):

Gravitational imaging and source reconstruction with luminous arcs

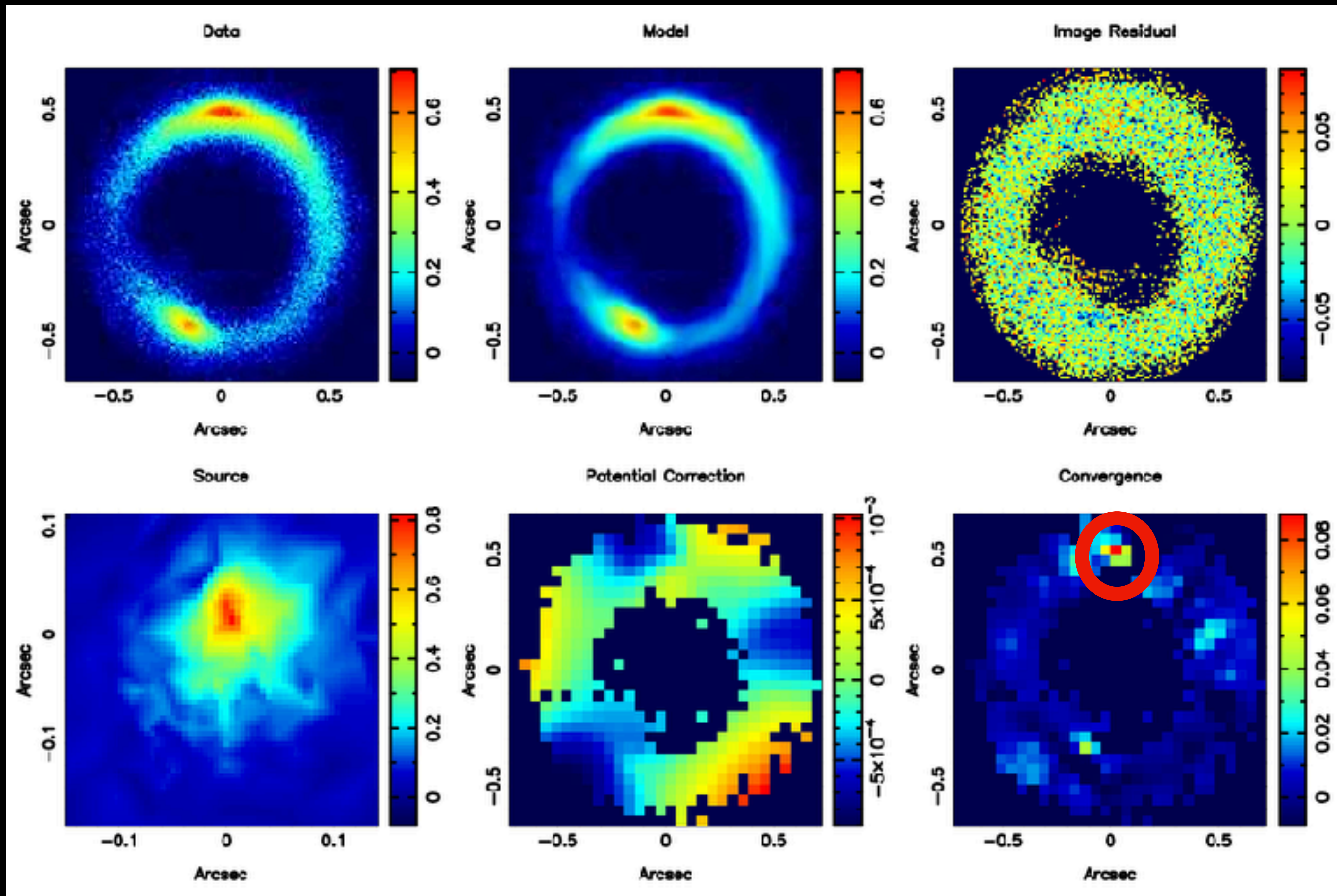
Gravitational imaging / source reconstruction



10^9 solar mass perturber

movie by Simon Birrer (UCLA)

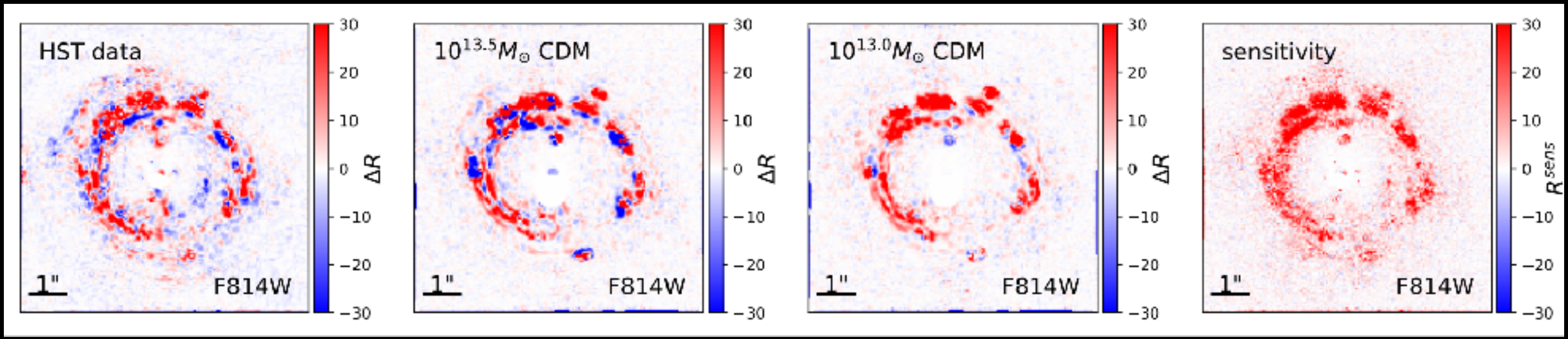
Gravitational imaging / source reconstruction (1)



adapted from Vegetti et al. 2012

- **detect individual halos at high confidence (see also Hezaveh et al. 2016)**
- **constrain the subhalo mass function (Vegetti et al. 2014, 2018)**

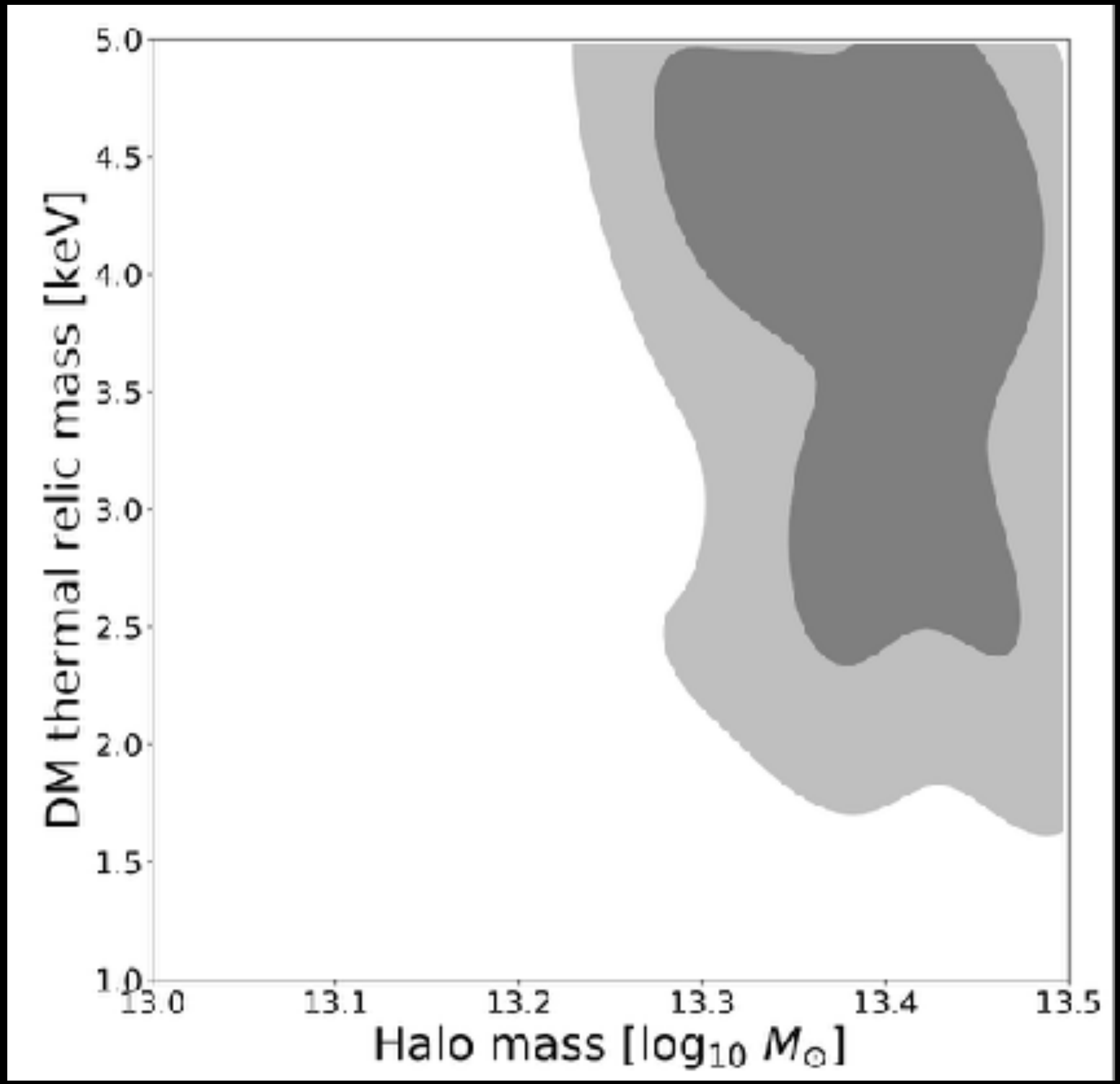
Gravitational imaging / source reconstruction (2)



figures adapted from Birrer et al. 2017

- can opt for a statistical analysis of surface brightness residuals in the Einstein ring

- Simultaneously infer halo mass and rule out certain warm dark matter models (see Birrer et al. 2017)



Multiple images arrive at different times:

theta : image plane coordinates
beta : source plane coordinates
psi : lens gravitational potential

$$t\left(\vec{\theta},\vec{\beta}\right) = \frac{D_t}{c}\left(\frac{1}{2}(\vec{\theta}-\vec{\beta})^2 - \Psi(\ \vec{\theta}\ )\right)$$

Observable: time delay

Depends on: gravitational potential

Fermat's Principle
-> light rays arrive at extrema of time delay surface

$$\vec{\beta} = \vec{\theta} - \frac{\partial\Psi(\ \vec{\theta}\ )}{\partial\vec{\theta}} = \vec{\theta} - \alpha(\ \vec{\theta}\ )$$

Observable: image positions

$$\vec{\theta}_l; \quad l = 1,2,3,4$$

Depends on: 1st derivative of potential

-global deflector mass profile

The lens equation is a mapping between image/source planes

Multiple images arrive at different times:

theta : image plane coordinates

beta : source plane coordinates

psi : lens gravitational potential

$$t\left(\vec{\theta},\vec{\beta}\right) = \frac{D_t}{c}\left(\frac{1}{2}(\vec{\theta}-\vec{\beta})^2 - \Psi(\ \vec{\theta}\ )\right)$$

Observable:

time delay

Depends on:

gravitational potential

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Observable:

image positions

$$\vec{\theta}_l;\quad l = 1,2,3,4$$

Depends on:

1st derivative of potential

-global deflector mass profile

Jacobian describes mapping between image/source planes

$$\begin{aligned} J_{ij} = \frac{\partial\beta_i}{\partial\theta_j} &= \delta_{ij} - \frac{\partial\alpha_i}{\partial\theta_j} \\ &= \delta_{ij} - \frac{\partial^2\psi}{\partial\theta_i\partial\theta_j} \end{aligned}$$

Observable:

image magnifications

$$M_l = \frac{1}{\det J(\vec{\theta}_l)}$$

Depends on:

2nd derivatives of potential

-sensitive to small scale structure near an image

Image flux ratios

Left:
simulation of 10^8 solar mass halo scanned over a lensed image

Subhalo 10,000 less massive than the main deflector changes image magnification
by 160%.

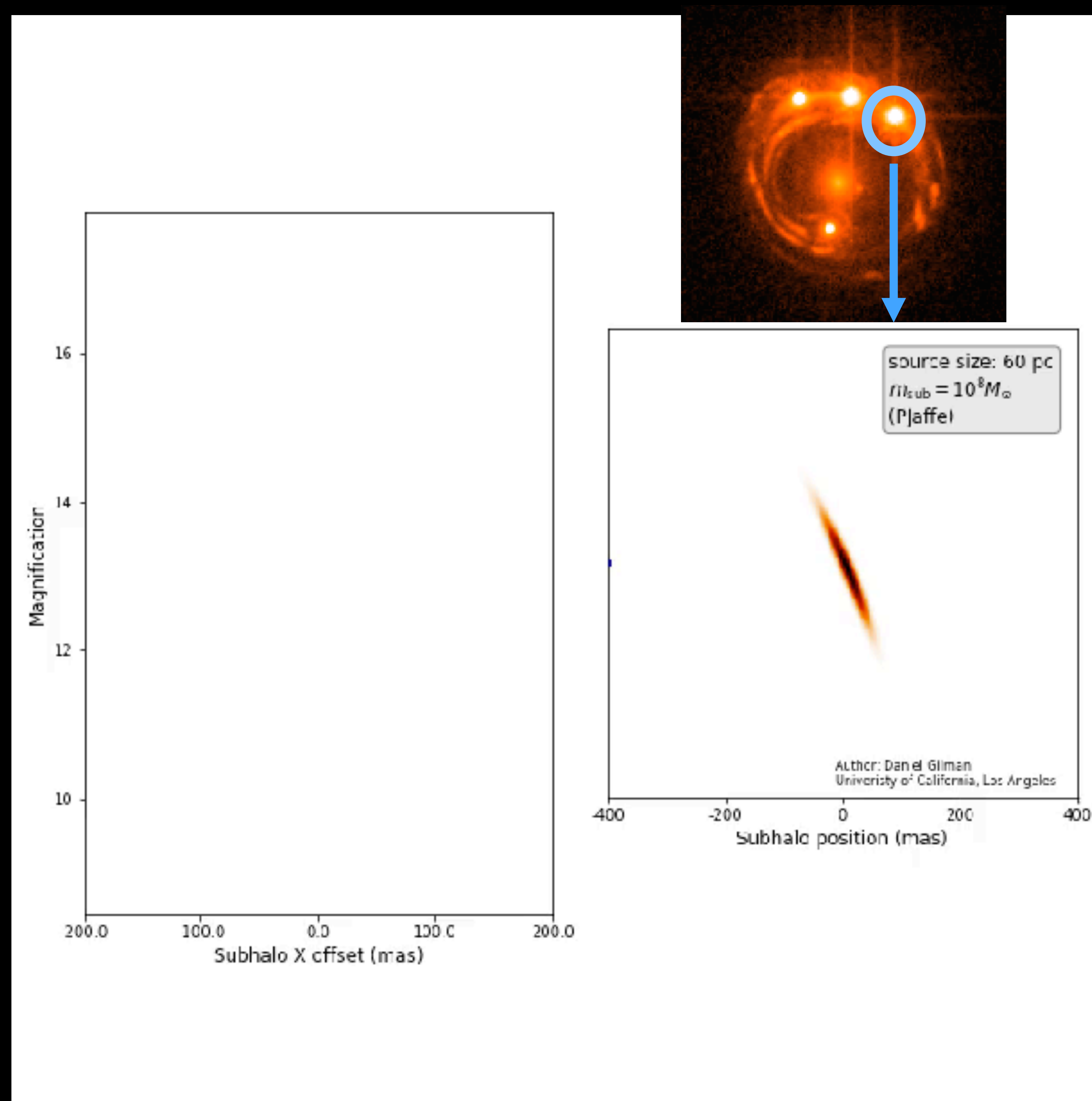
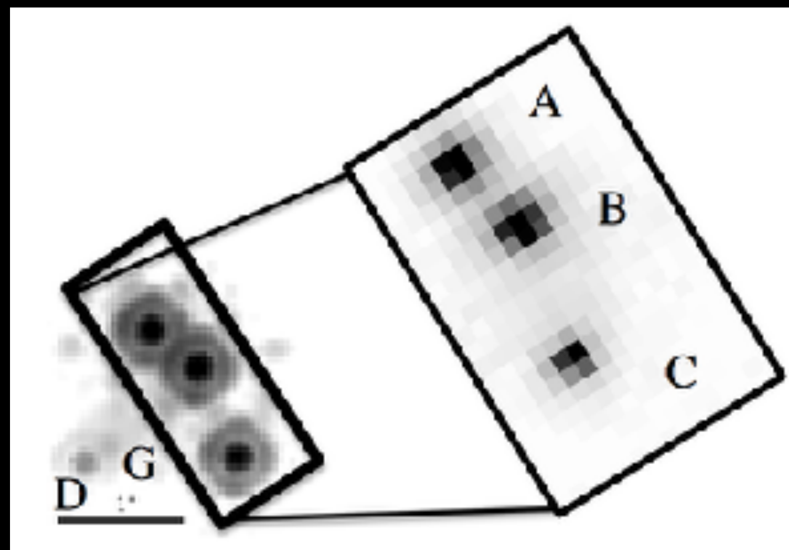
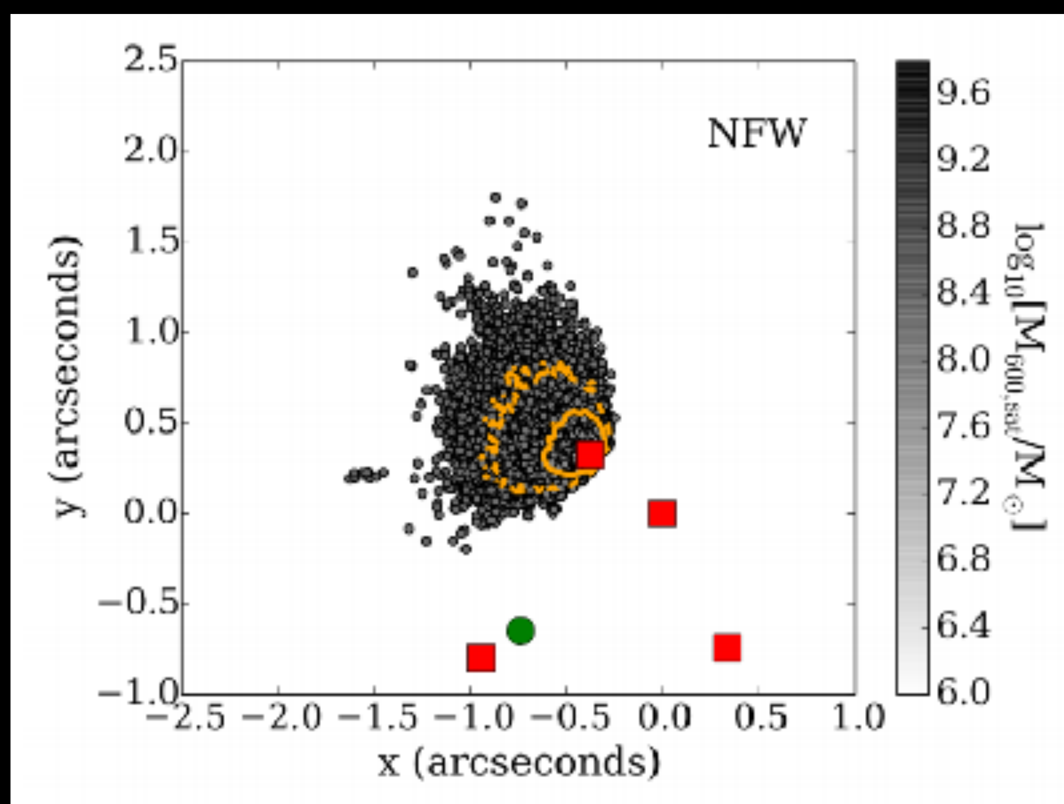


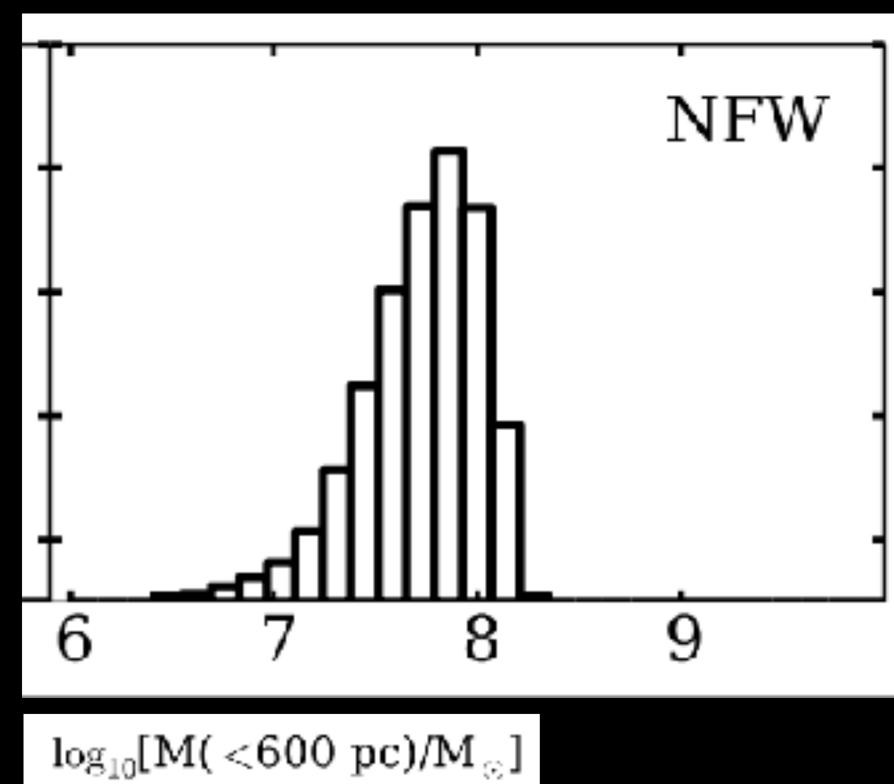
Image flux ratios



Some lenses do not have a visible extended arc
e.g. B1422+231

- use the fluxes of multiple images as constraints





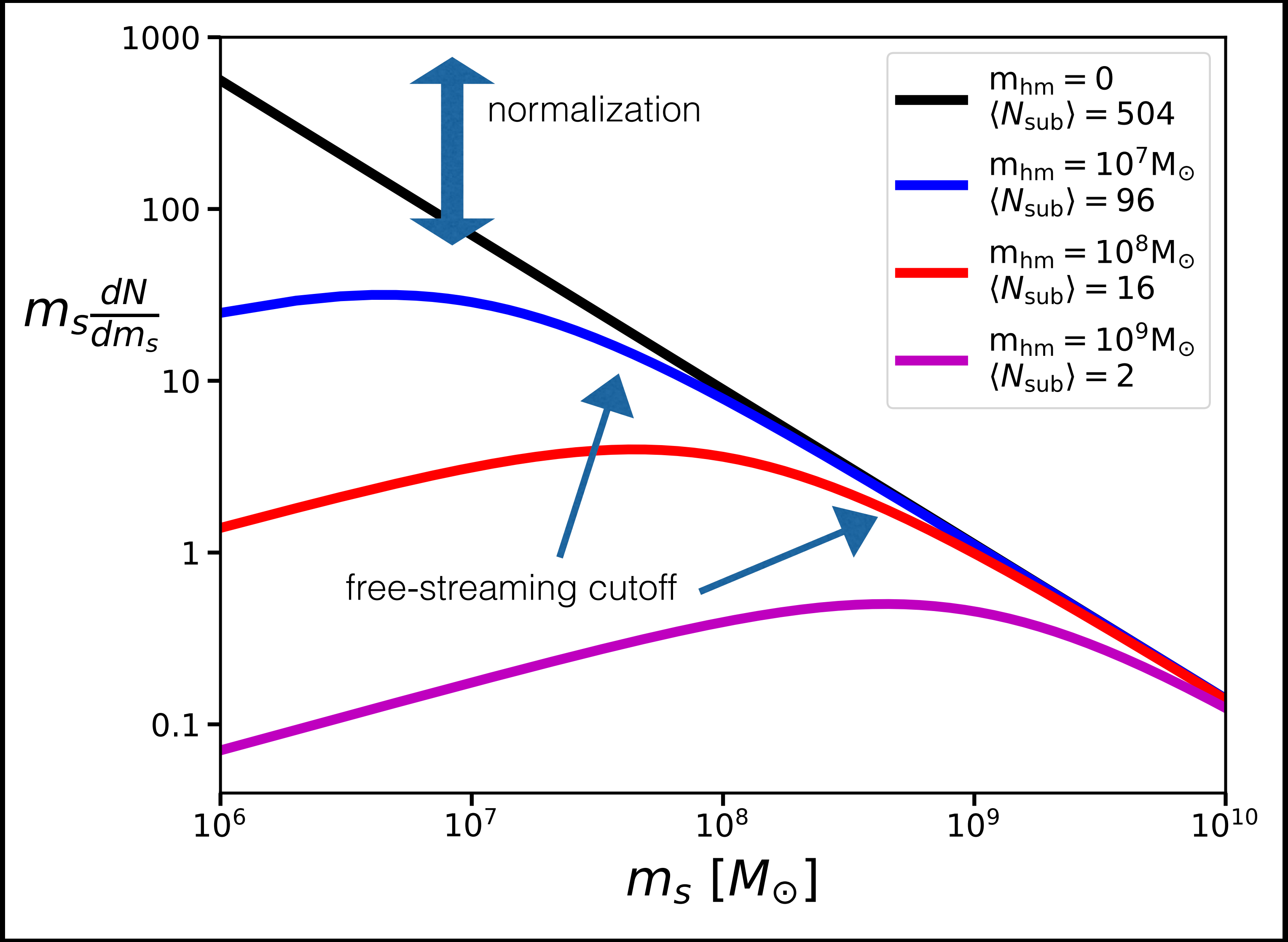
figures adapted from Nierenberg et al. 2014

Can infer the presence of a subhalo near one of the images using magnifications, positions

A (new) statistical approach: forward modeling image flux ratios

Dark matter models predict thousands of subhalos which together produce non-linear effects in magnifications

Goal: model the substructure content of lenses, and forward model flux ratio *statistics* will full substructure realizations

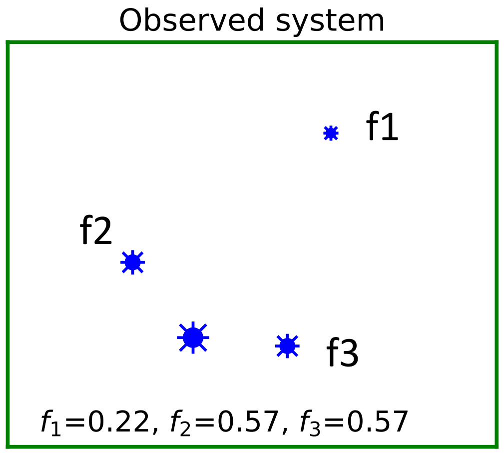


Toy model:

- subhalo mass function characterized by normalization, free streaming cutoff (half mode mass: *m_hm*)
- subhalo density also changes

Forward modeling procedure

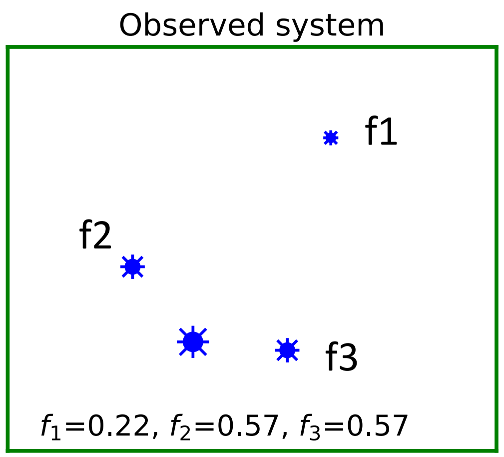
Forward modeling flux ratios step-by-step (1)

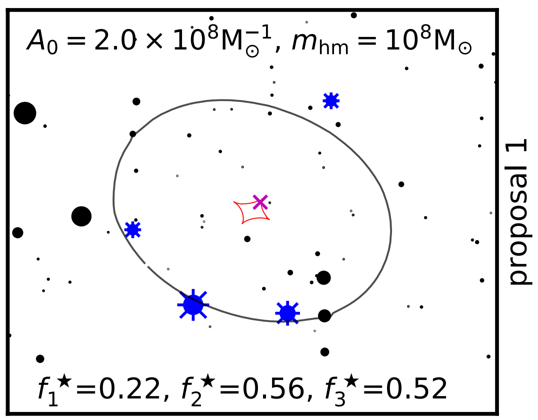


1. observe positions, time delays, flux ratios

Forward modeling procedure

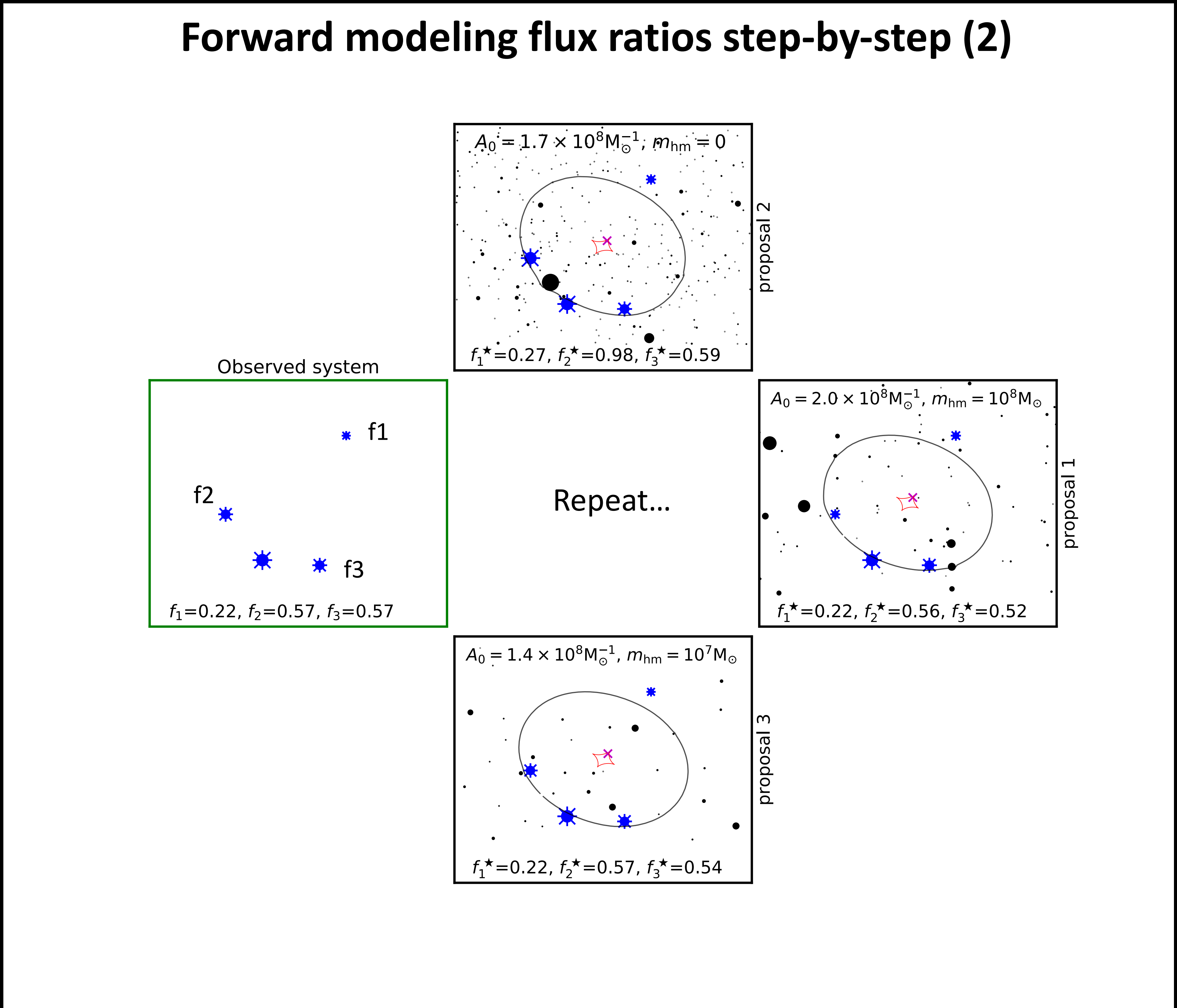
Forward modeling flux ratios step-by-step (2)





1. observe positions, time delays, flux ratios
2. Render substructure realization

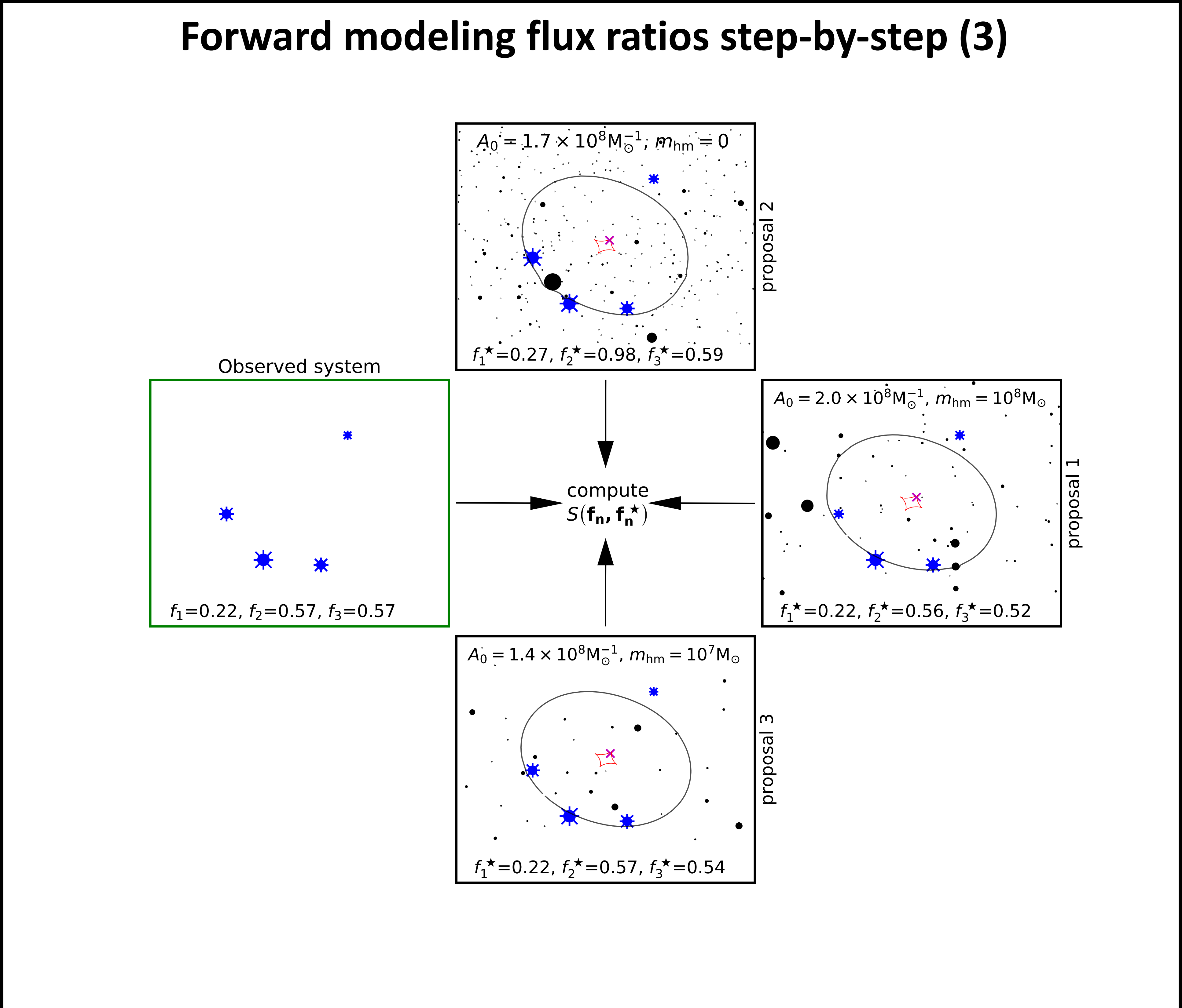
Forward modeling procedure



1. observe positions, time delays, flux ratios
2. Render substructure realization
3. repeat 10^6 times per lens…

5.

Forward modeling procedure



1. observe positions, time delays, flux ratios
2. Render substructure realization
3. repeat 10^6 times per lens…
4. compute a summary statistic:

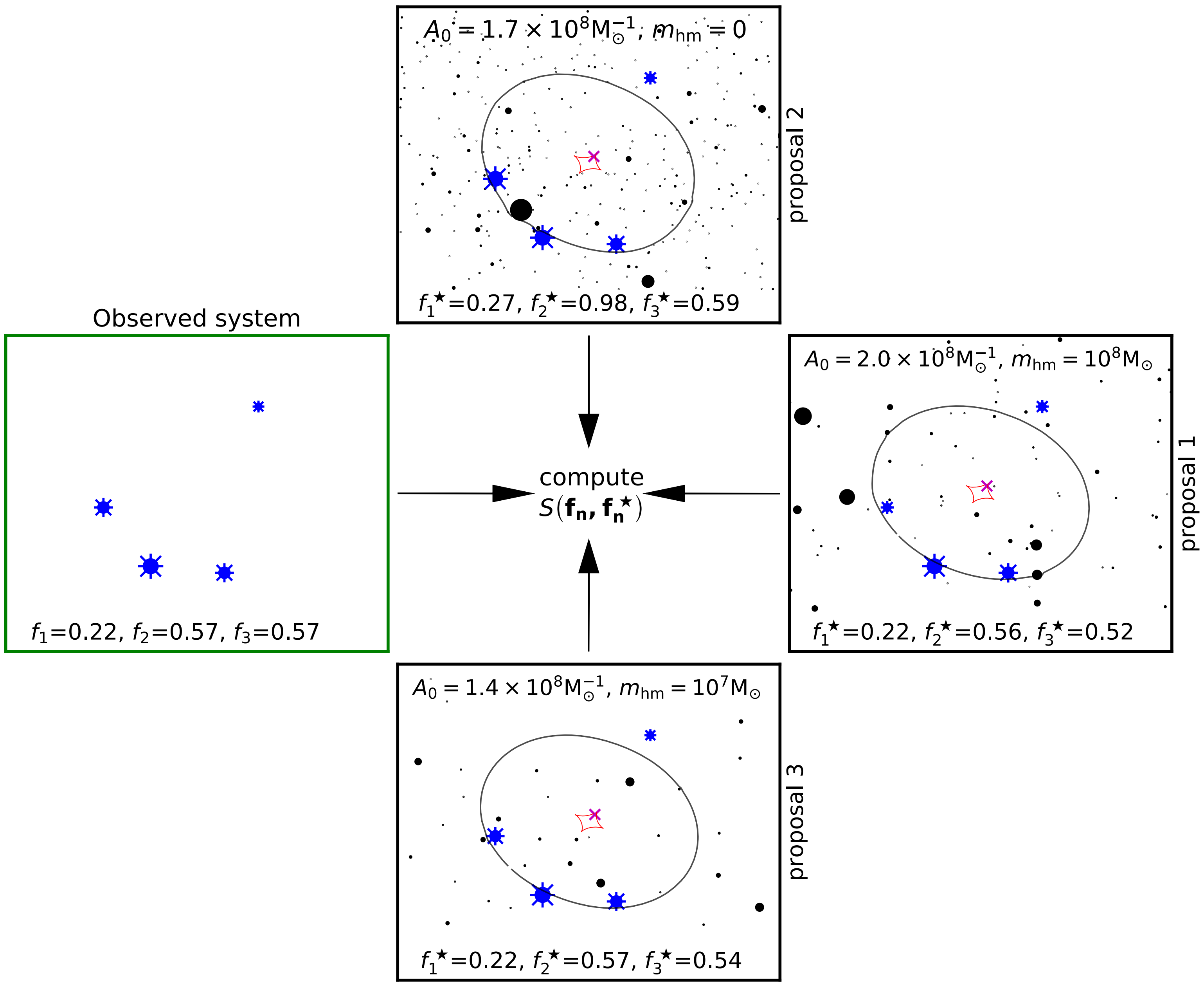
$$S\left(\mathbf{f_n}, \mathbf{f_n}^\star\right) = \sqrt{\sum_{i=1}^{3} \left(f_{n(i)} - f^\star_{n(i)}\right)^2}$$

observed flux ratio

model flux ratio

Forward modeling procedure

Forward modeling flux ratios step-by-step (3)



1. observe positions, time delays, flux ratios
2. Render substructure realization
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observed flux ratio

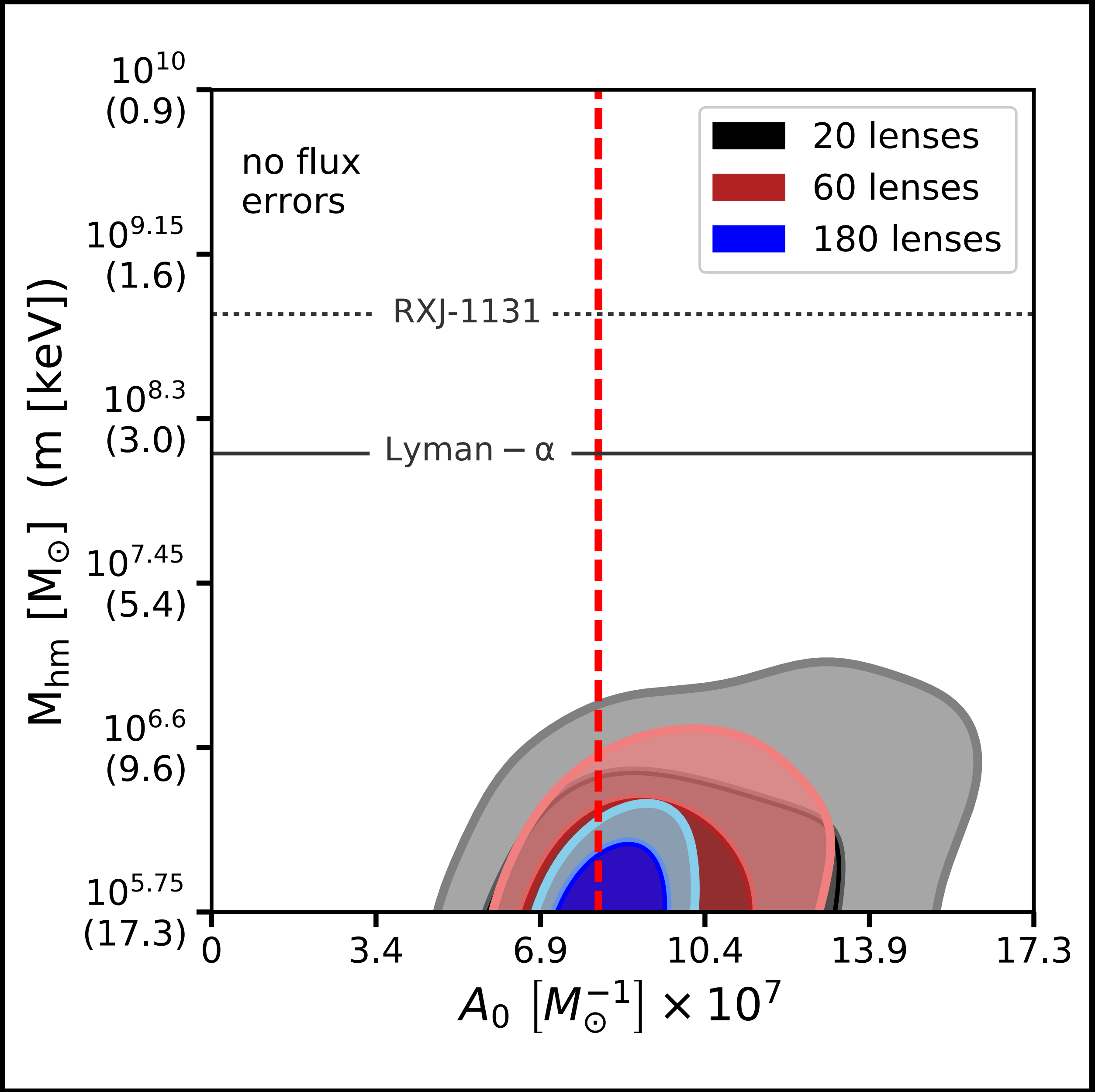
model flux ratio

5. select models based on summary statistic

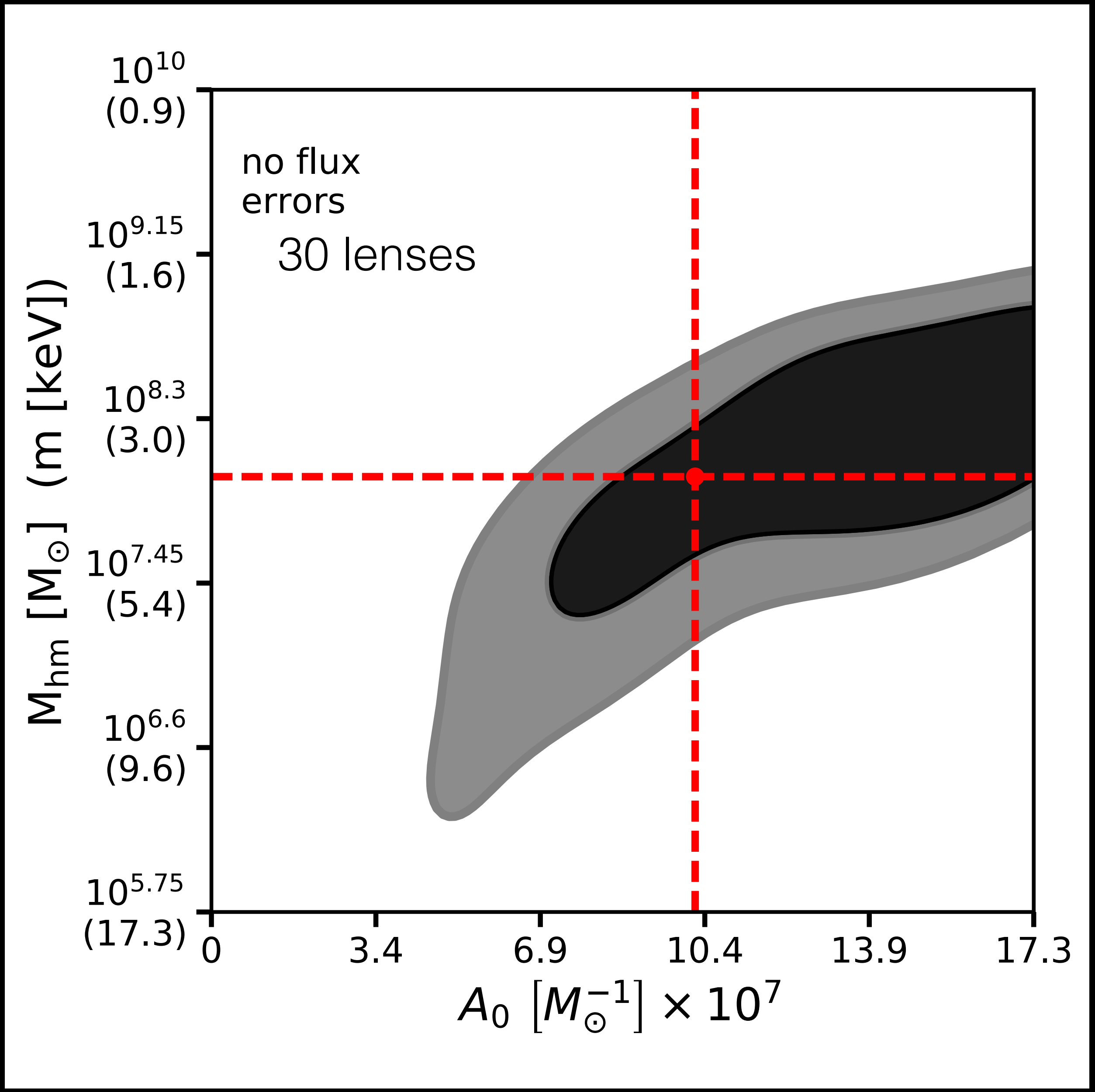
Does this method work, in principle?

(perfect model, perfect measurements)

Input Cold Dark Matter



Input Warm Dark Matter



figures from Gilman et al 2018

The effect of systematic errors in fluxes

- our lens models and measurements will not be perfect
- what happens when we lose sensitivity to fluxes at ~few% level?

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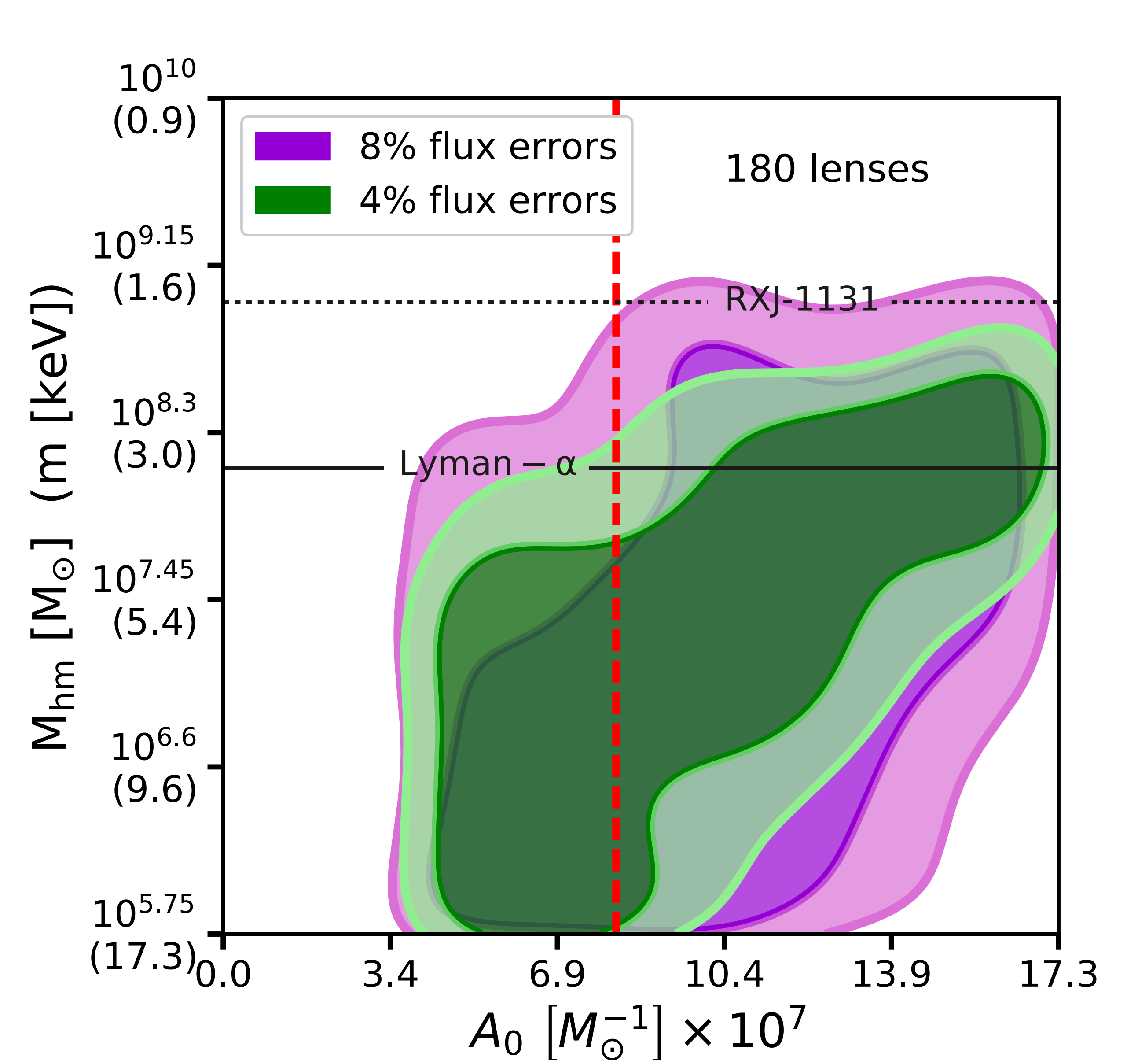
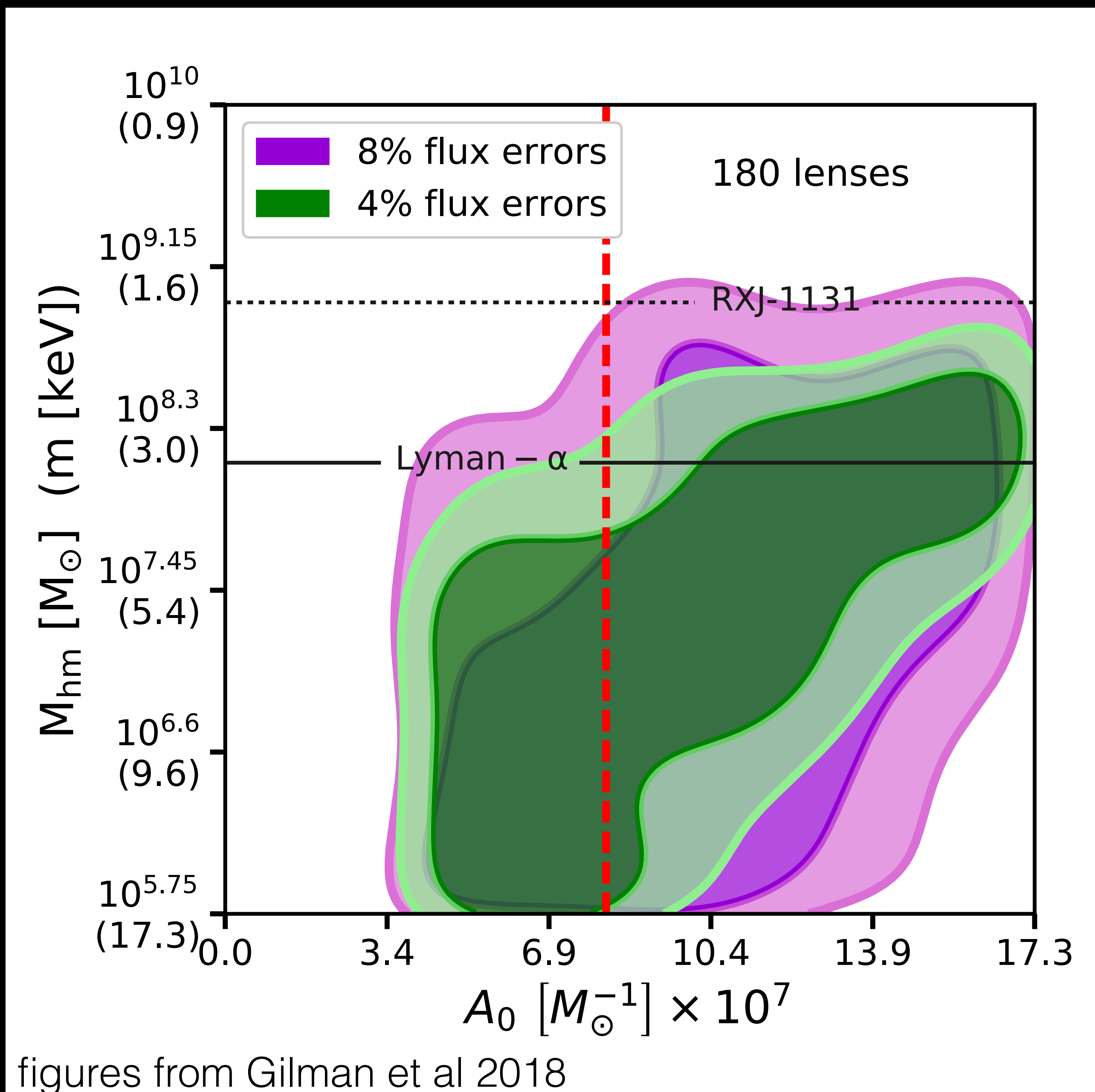


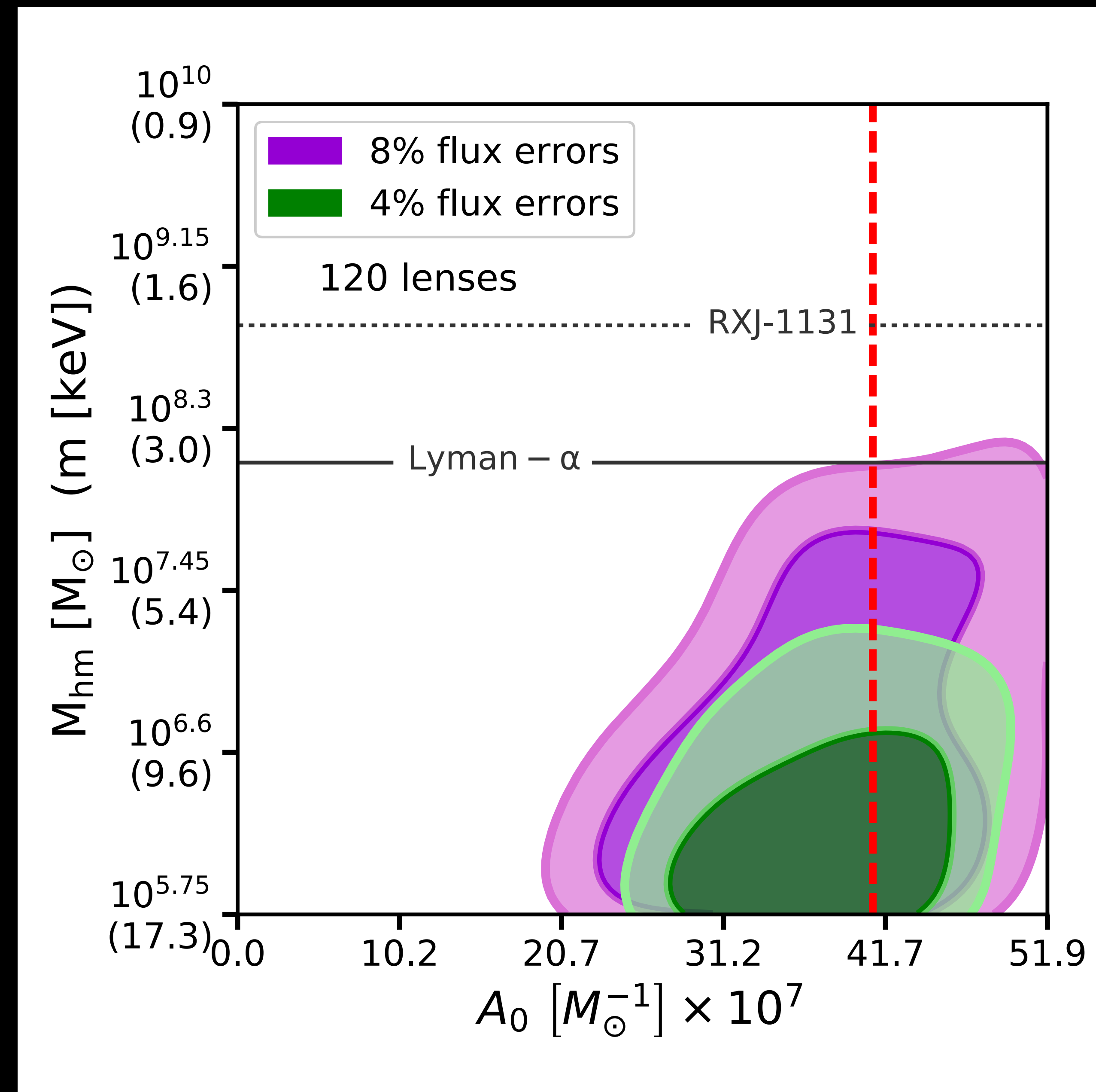
figure from Gilman et al 2018

Case 1: low normalization (few subhalos)

The effect of systematic errors in fluxes

- our lens models and measurements will not be perfect
- what happens when we lose sensitivity to fluxes at ~few% level?



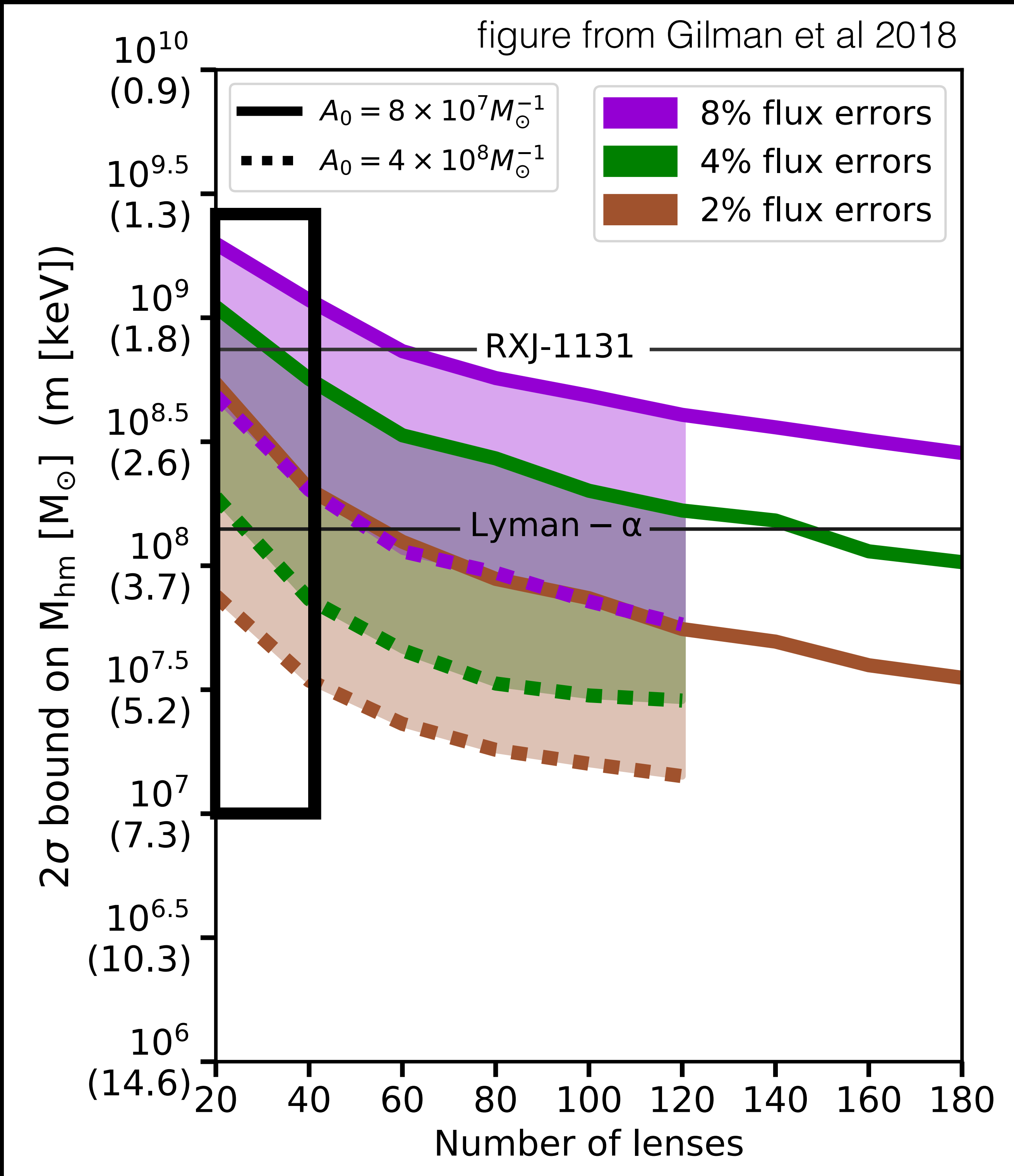


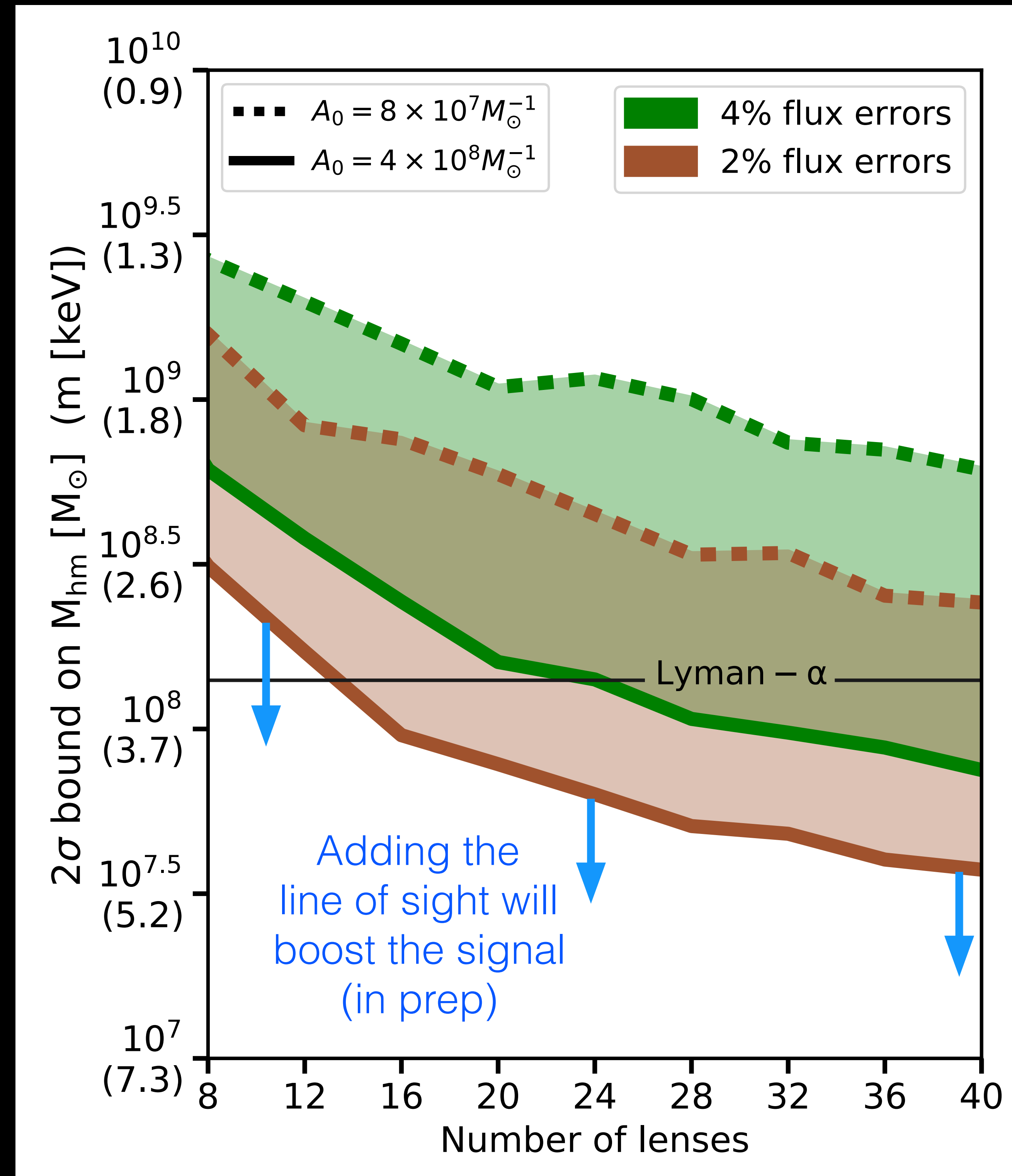
Case 1: low normalization (few subhalos)

Case 2: high normalization

Interpretation: information content scales with the normalization

Future projections



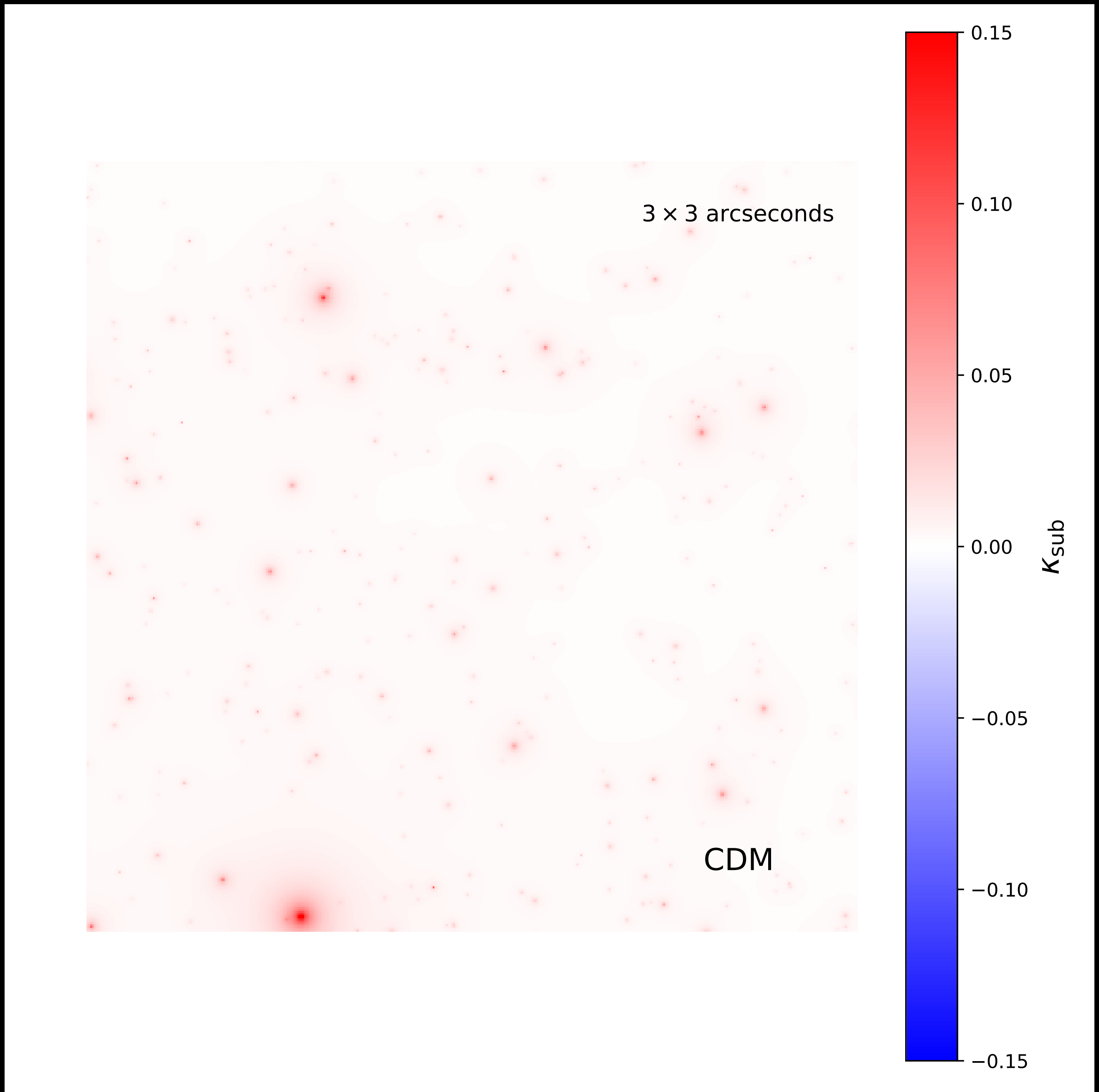


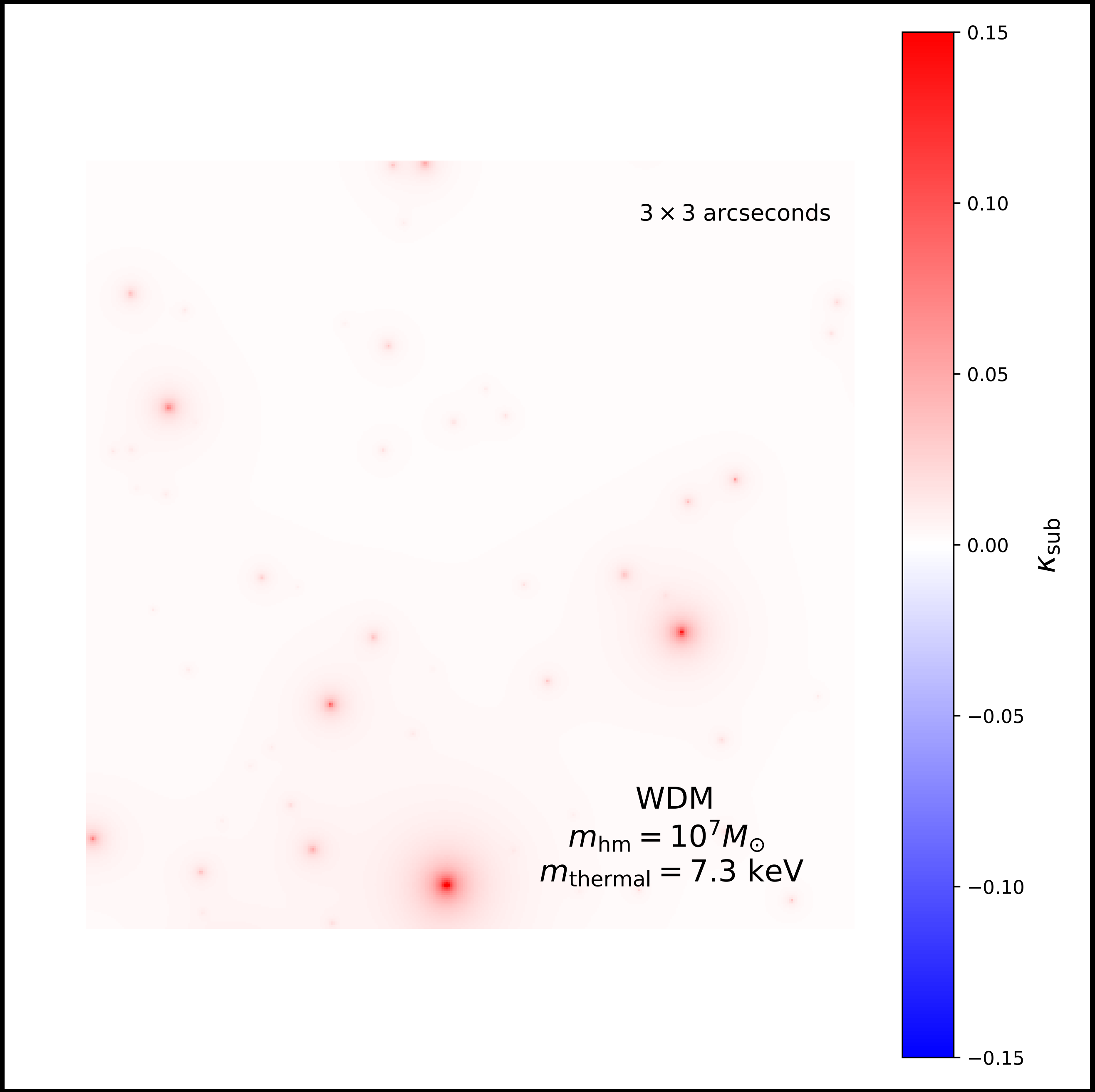
Next step:

modeling of foreground/background halos and their non-linear effects

modeling the line of sight (work in progress)

single plane
in projection

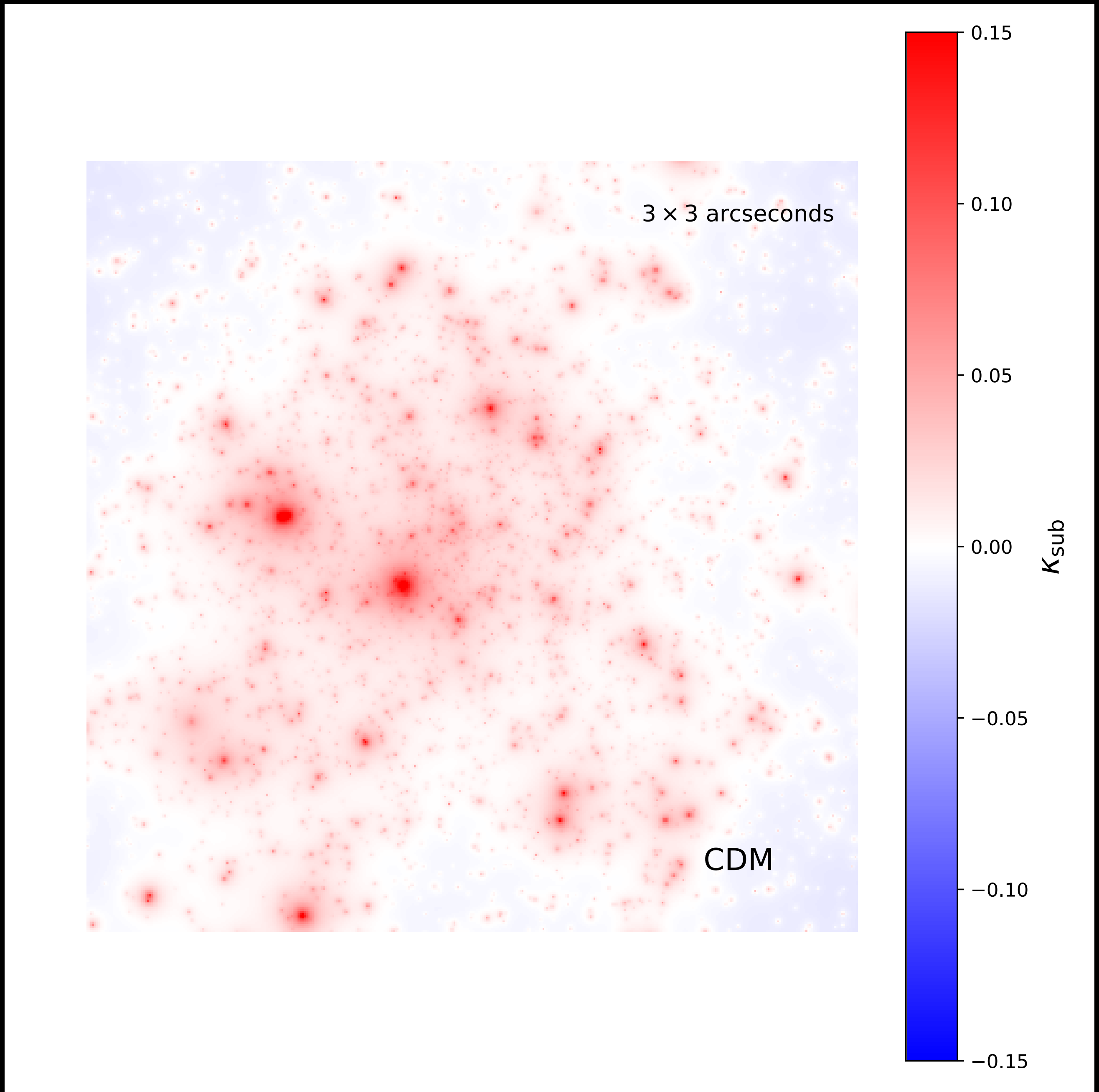


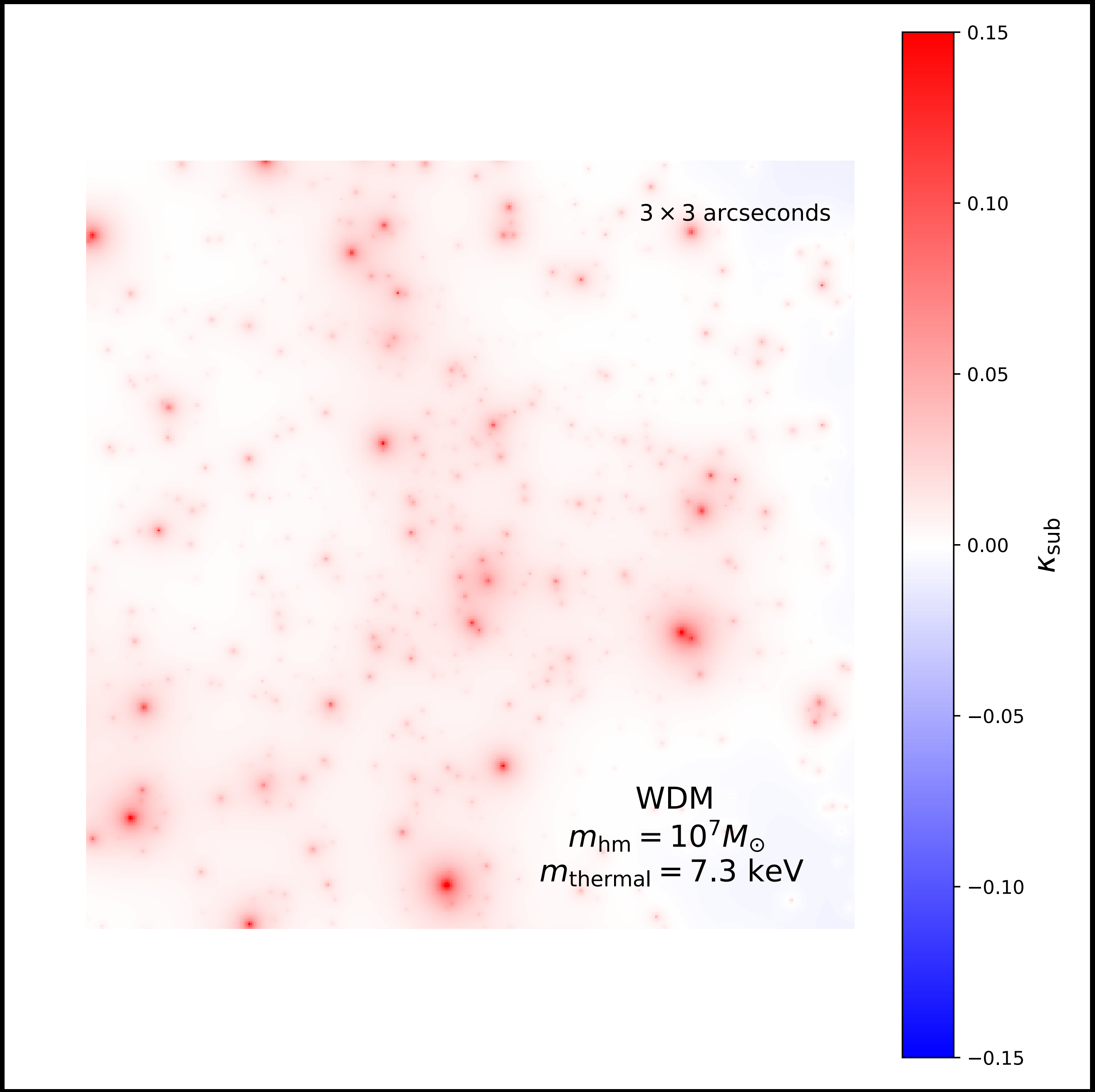


Projected (single plane)

modeling the line of sight (work in progress)

Full line of sight + single plane in projection

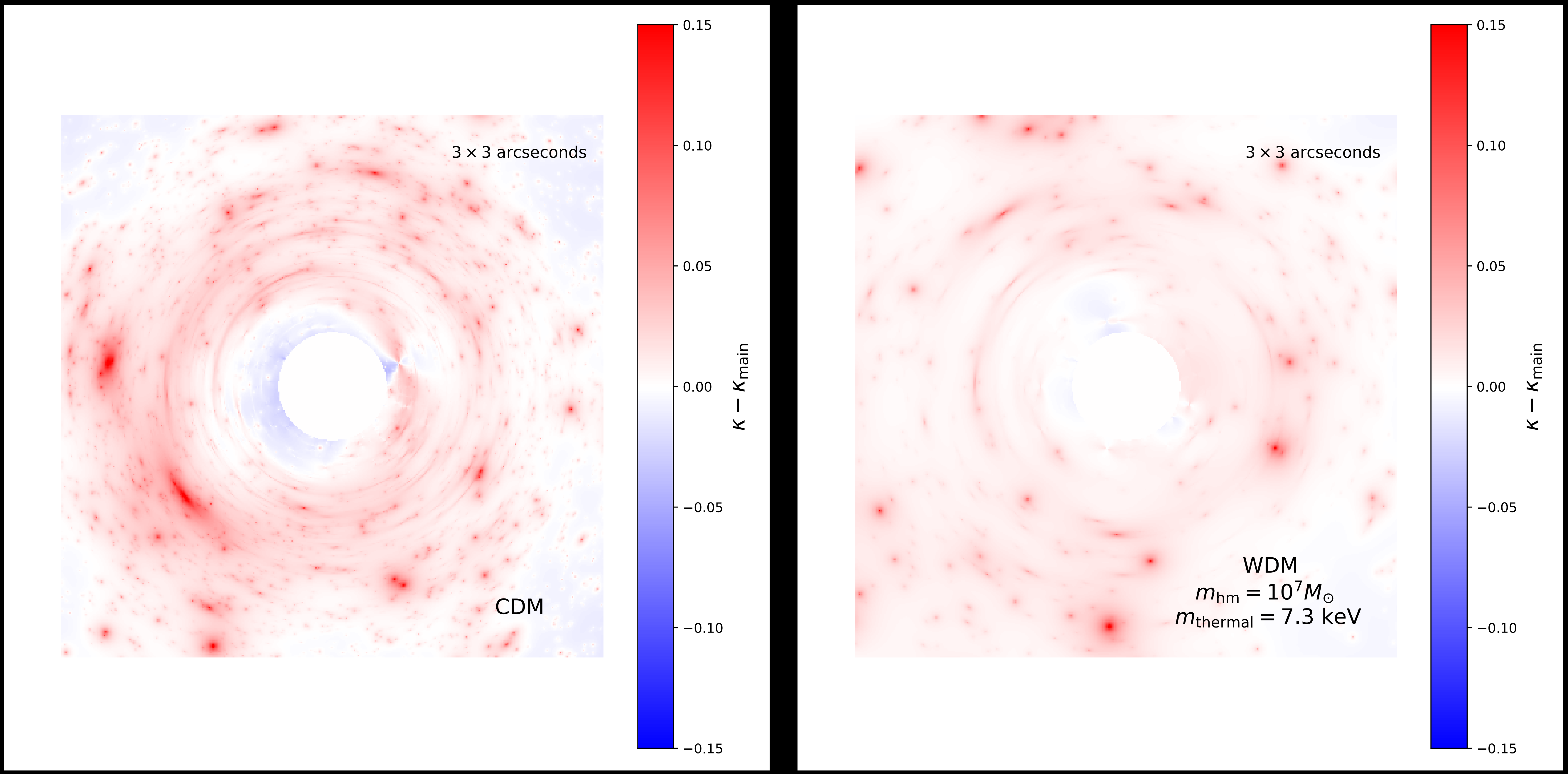




Projected (multi-plane)

modeling the line of sight (work in progress)

effective single plane mass distribution



Projected (multi-plane nonlinear)

Tweetable Conclusion

#Stronglensing probes mass distributions on small scales. With a sample of O(10) lenses, we can measure the shape and amplitude of the subhalo mass function and learn about the properties of #darkmatter.

Thanks!

R_cusp/R_fold/(R_cross?) statistic

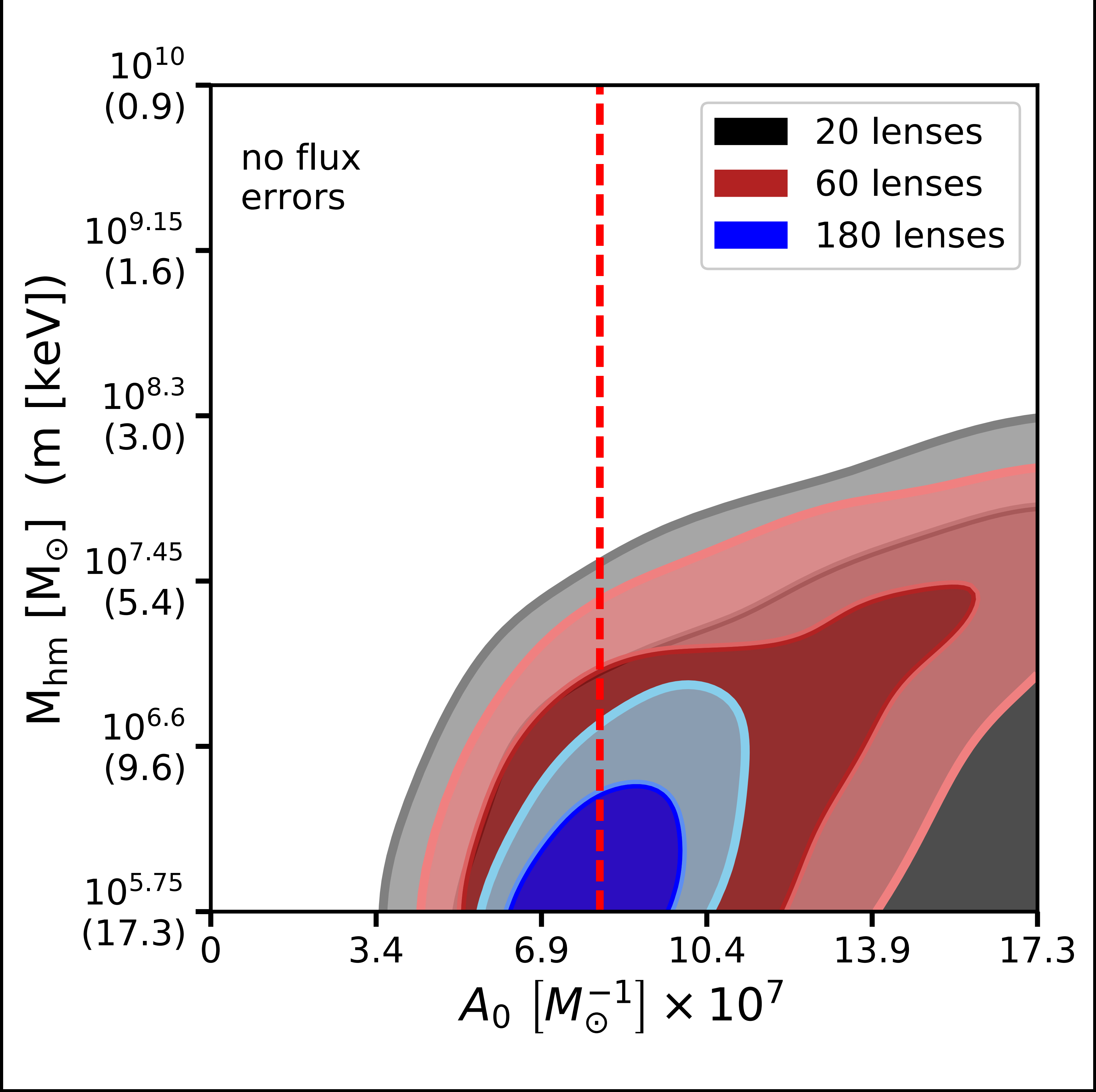


Image configuration